# IIT RESEARCH INSTITUTE

VOLUME I

CIVIL DEFENSE SHELTER OPTIONS:
DELIBERATE SHELTERS

Final Report

OCD Contract DAHC-68-C-0126
OCD Work Unit 1614D

December 1971

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The survivability ratings have a bilinear form and therefore depend, for the most part, on the protectability of a single structural component; in this case the arch shell. They are also sensitive to the duration of the blast.

It will be noted that the fallout shelter (Fig. S-2a) is very similar in its protectability to the 10 psi blast shelter (Fig. S-2b). In fact the two survivability ratings are identical. It is often difficult to design a fallout-only shelter and not to introduce some level of blast resistance. This is especially difficult if the structural system is as favorable as a buried arch. The use of such shelters in the planning of a shelter system could grossly underestimate its performance if the rating is not known.

In addition to the closed shelters described, open shelters were also considered in this study. The influence of this effect on survivability is discussed.

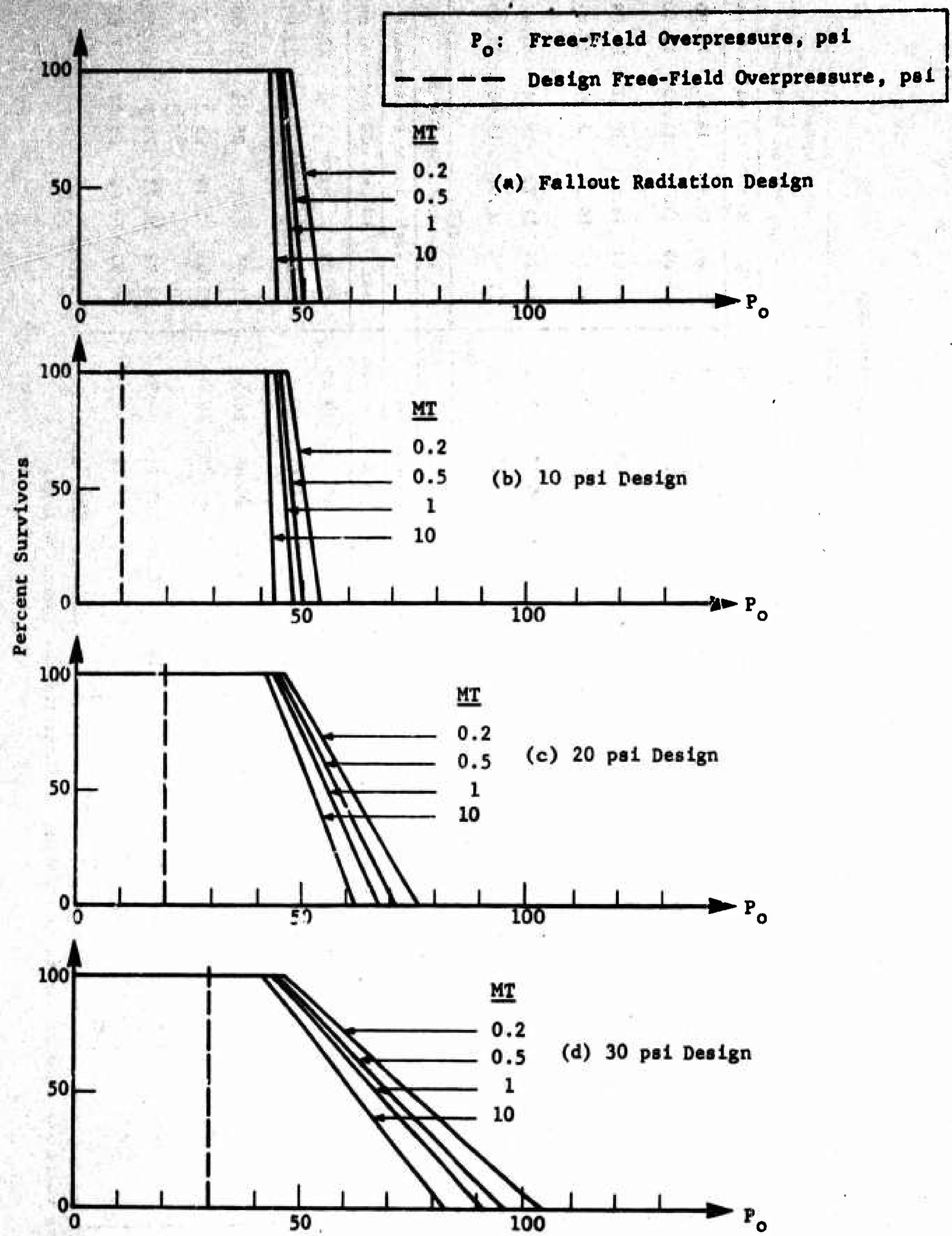


Fig. S-2 PEOPLE SURVIVABILITY (RC ARCH SHELTERS)
LOW LEVEL WEAPON EFFECTS DESIGNS

TABLE S-3

SUMMARY OF SINGLE-PURPOSE SHELTER COSTS PER SQUARE FOOT OF SHELTER AREA

| Type of Structure | Capacity (No. of Persons) | Cost Option 1 | | | | Cost Option 2 | | | | Cost Option 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Design Weapon Environment | | | | Design Weapon Environment | | | | Design Weapon Environment | | | |
| | | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi |
| R/C Arch | 500 | 10.85 | 11.08 | 11.88 | 12.20 | 11.15 | 11.38 | 12.19 | 12.51 | 15.60 | 15.83 | 16.63 | 16.95 |
| | 1000 | 10.30 | 10.56 | 11.07 | 11.65 | 10.61 | 10.86 | 11.38 | 11.95 | 15.05 | 15.31 | 15.83 | 16.40 |
| Steel Arch | 500 | 10.16 | 11.85 | 13.57 | 19.34 | 10.46 | 12.16 | 13.88 | 19.64 | 14.91 | 15.61 | 18.32 | 24.09 |
| | 1000 | 9.51 | 11.59 | 13.31 | 19.06 | 9.82 | 11.89 | 13.62 | 19.36 | 14.27 | 16.34 | 18.06 | 23.81 |
| R/C Rectangular | 500 | 10.93 | 12.94 | 15.12 | 19.14 | 11.20 | 12.11 | 15.40 | 19.41 | 15.21 | 17.22 | 19.41 | 23.42 |
| | 1000 | 9.76 | 11.74 | 13.77 | 17.40 | 10.03 | 12.01 | 14.05 | 17.68 | 14.04 | 16.02 | 18.06 | 21.69 |

| Type of Structure | Capacity (No. of Persons) | Cost Option 4 | | | | Cost Option 5 | | | | Cost Option 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Design Weapon Environment | | | | Design Weapon Environment | | | | Design Weapon Environment | | | |
| | | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi |
| R/C Arch | 500 | 17.83 | 18.06 | 18.87 | 19.19 | 18.14 | 18.37 | 19.17 | 19.49 | 22.59 | 22.81 | 23.62 | 23.94 |
| | 1000 | 17.54 | 17.80 | 18.32 | 18.89 | 17.85 | 18.10 | 18.62 | 19.20 | 22.30 | 22.50 | 23.07 | 23.64 |
| Steel Arch | 500 | 17.17 | 18.84 | 20.56 | 26.33 | 17.45 | 19.14 | 20.86 | 26.63 | 21.90 | 23.59 | 25.31 | 31.08 |
| | 1000 | 16.76 | 18.83 | 20.55 | 26.30 | 17.06 | 19.13 | 20.86 | 26.60 | 21.51 | 23.58 | 25.31 | 31.05 |
| R/C Rectangular | 500 | 18.44 | 20.45 | 22.64 | 26.65 | 18.71 | 20.72 | 22.91 | 26.92 | 22.72 | 24.73 | 26.92 | 30.93 |
| | 1000 | 15.67 | 17.65 | 19.69 | 23.31 | 15.94 | 17.92 | 19.96 | 23.59 | 19.95 | 21.93 | 23.97 | 27.60 |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

TABLE S-2

SHELTERING COST OPTIONS FOR SINGLE-PURPOSE SHELTERS

(Cost Items Comprising Sheltering Options Considered)

| Cost Option | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| Site Clearance | Site Clearance | Site Clearance | | | |
| Access Road | Access Road | Access Road | | | |
| Shelter Structure | Shelter Structure | Shelter Structure | | | |
| Entranceway | Entranceway | Entranceway | | | |
| — | OCD Ventilation Package | Ventilation* System | Same as Option 1 | Same as Option 2 | Same as Option 3 |
| — | OCD Water Package | Water Supply* System<br>Toilet System* | | | |
| — | OCD Electrical | Wiring, Fixtures and Outlets* | | | |
| — | — | Partitions | | | |
| — | — | — | Parking Lot | Parking Lot | Parking Lot |

*commercial items

TABLE S-1

SUBJECT SHELTERS

| Category | Shelter Description | Shelter Capacity No. of Persons | Design Weapon Environment | Pricipal Materials of Construction | Location Relative to Ground Surface | No. of Shelters Considered |
|---|---|---|---|---|---|---|
| Single-Purpose | RC Arch | 500 & 1000 | Fallout, 10, 20 & 30 psi | RC & soil | Semiburied | 4 |
| | RC Arch | 500 | 100 & 150 psi | RC & soil | Semiburied | 2 |
| | Steel Arch | 500 & 1000 | Fallout, 10, 20 & 30 psi | RC, steel & soil | Semiburied | 4 |
| | Rectangular Shelter | 500 & 1000 | Fallout, 10, 20 & 30 psi | RC & soil | Semiburied | 4 |
| Dual-Purpose | Blast Resistant School Basements | 550 & 1100 | 5, 25 & 50 psi | RC | Below Grade | 6 |
| | Parking Garage | 5000 | 5, 25, & 50 psi | RC | Below Grade | 3 |
| | Expressway Grade Separation | 800 | 5, 25, & 50 psi | RC | Above and Below Grade | 3 |
| | Subway Station | 4670 | N/A | RC | Below Grade | 1 |

RC - reinforced concrete

Single-purpose shelters include:

- Reinforced concrete and steel arch structures
- Reinforced concrete rectangular structures

Dual-purpose shelters include:

- School basements
- Below-grade parking garages
- Grade-separation shelters
- Subway station

Shelters considered are summarized in Table S-1. With the exception of the subway station (Washington D.C. Metropolitan Transit System) all of these shelters are conceptual studies and therefore don't exist in any real sense. They have been designed in all necessary detail and are described with cost (sheltering) options and corresponding costs.

Several cost options were defined and costed for each shelter type. Six different cost options were considered for single-purpose shelters. These are identified in Table S-2. Corresponding unit sheltering costs for several single-purpose shelters are given in Table S-3. Different sheltering options were used for dual-purpose shelters. The differences reflected the primary function of the structure and thus the availability of existing support equipment. Sheltering options and costs for this category of shelters are also given.

The analysis of people survivability was performed in two parts. The first part was concerned with determining the response of the shelter structure when subjected to a range of overpressure levels. The second part was concerned with relating the response of the structure at each overpressure level to people survivability. Typical results are illustrated in Fig. S-2 and represent the protective capabilities of closed reinforced concrete arch shelters against the effects of blast. Four weapon sizes (0.2, 0.5, 1 and 10 MT) are considered.

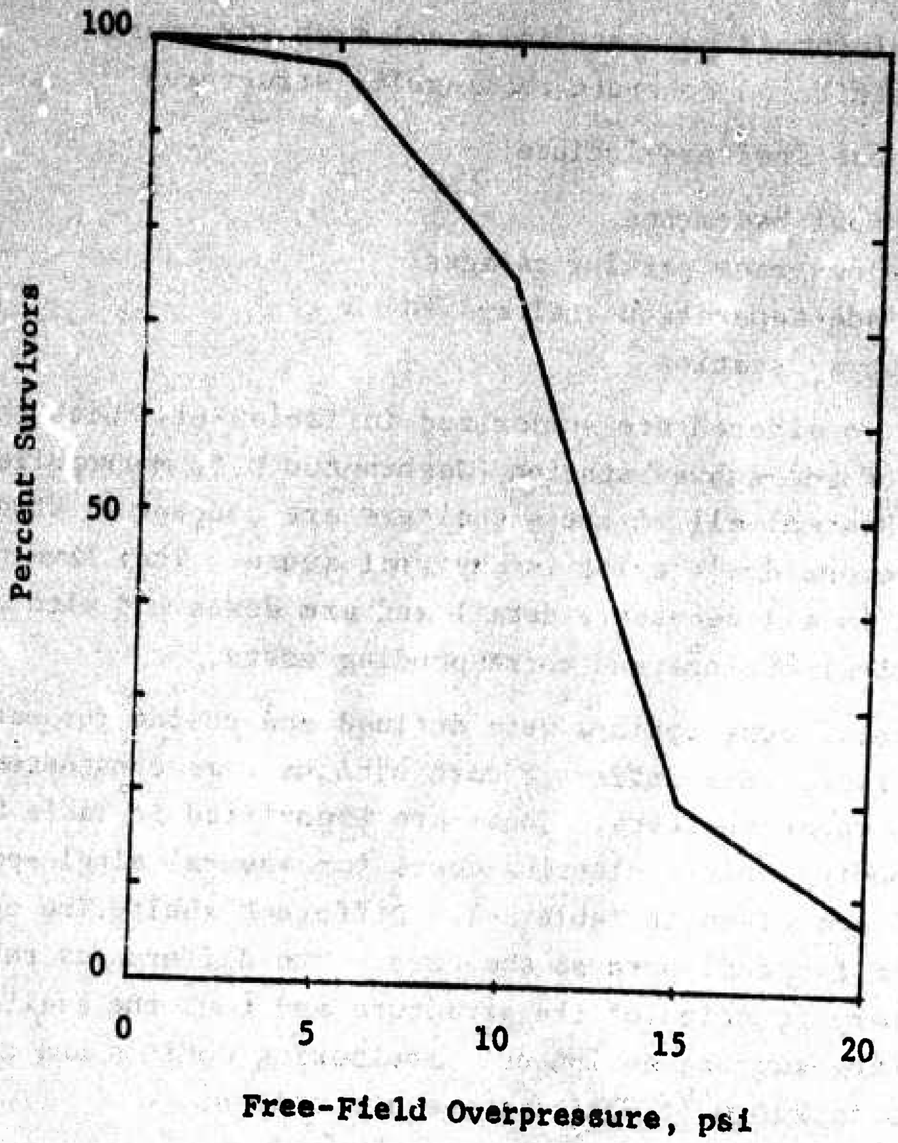


Fig. S-1 SURVIVABILITY RATING (Estimate of People Survivability in a Shelter Structure)

Results of full-scale field tests suggest that this type of rating system is a poor indicator of overall shelter effectiveness in most cases studied. Such results show that typical, deliberate shelter concepts (buried arches, basements, etc.) are often 100 percent effective at overpressure levels significantly greater than those they were designed to resist. A great deal depends on whether the shelter is buried and on the type of structural system employed. For example, a two-way concrete slab is more effective than a flat plate.

In any shelter system, reliable knowledge of expected performance for all structures comprising it is extremely important. Without such knowledge, effectiveness and cost of the system may be grossly over- or underestimated. To avoid this difficulty, the planner of shelter systems needs at his disposal reliable and readily usable information in these two categories:

- Sheltering Options
- Survivability Ratings

A sheltering option is defined to include a shelter structure and any equipment and/or supplies necessary in order to achieve a specified level of protection. It should be described in terms of all pertinent physical characteristics including costs.

A survivability rating may be defined as a mathematical means for representing the protective capability of a given shelter when subjected to a range of weapon environments. Formulation requires an analysis capable of considering all pertinent weapon effects acting on the shelter and predicting the number of survivors. Central to such an analysis is the accurate description of the weapon environment within the shelter and the corresponding response of shelterees. A typical survivability rating is shown in Figure S-1.

Shelters considered in this study fall into two categories i.e., single- and dual-purpose.

## SUMMARY

## CIVIL DEFENSE SHELTER OPTIONS: DELIBERATE SHELTERS


The objective of this study was to:

1. Investigate the survivability potential for people located in selected classes of deliberate personnel shelters when subjected to the effects of nuclear weapons.

2. Determine sheltering costs for several feasible shelter options.

3. Select a rating system, which includes "people survivability" and "sheltering costs", whereby the performance of personnel shelters in a nuclear weapon environment may be rated and compared in a consistent and rational manner.

Deliberate personnel shelters are those structures which have been specifically designed with blast and/or fallout protection in mind. They may be single- or dual-purpose types. A dual-purpose shelter is one which in addition to performing its primary function (school, office etc.) is also capable of providing protection in the event of an emergency. The sole and only function of a single-purpose shelter is to provide protection.

Prior to completion of this study a rational rating system for "deliberate personnel shelters" did not exist. It has been customary to design a shelter and rate it on the basis of the weapon environment it was designed to resist. Such rating (designation) usually consists of an overpressure level (free field), fallout protection factor (PF) and weapon size. The implication being that for the given weapon environment, the shelter is 100 percent effective in providing protection. Such a rating system is useful but incomplete, since it provides no indication of performance at higher overpressure levels, different weapon sizes and multiple attack conditions. This also provides no readily usable information on fire and prompt nuclear radiation resistance.

SUMMARY

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A. Longinow
J. Kalinowski
C. A. Kot
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for

Office of Civil Defense
Office of the Secretary of the Army
Washington, D.C. 20310

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13. ABSTRACT

The ability of specific shelter structures to provide protection for personnel subjected to nuclear weapon environments is investigated and respective sheltering costs are estimated. Specific structures considered and costs for several defined sheltering options are given, and the capability of these shelters in providing protection relative to a range of weapon environments is presented. The bases for these predictions are described.

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# FOREWORD

This final report on IIT Research Institute Project J6144, Contract DAHC-68-C-0126, OCD Work Unit 1614D, entitled "Civil Defense Shelter Options: Deliberate Shelters," is presented in two volumes. The work was performed in the Structural Analysis Section, Engineering Mechanics Division of IITRI by A. Longinow, A. J. Kalinowski, C. A. Kot and F. Salzberg. It was monitored by Mr. C. D. Kepple of the Shelter Research Division, Office of Civil Defense.

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The ability of specific shelter structures to provide protection for personnel subjected to nuclear weapon environments is investigated and respective sheltering costs are estimated. Specific structures considered and costs for several defined sheltering options are given, and the capability of these shelters in providing protection relative to a range of weapon environments is presented. The bases for these predictions are described.

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# CHAPTER ONE

## PERSONNEL SURVIVABILITY IN DELIBERATE SHELTERS

When it becomes necessary to protect a segment of the population against a specified nuclear attack (weapon environment), it is first desirable to select and describe a number of distinct, alternative ways whereby this protection may be obtained and then to estimate the cost and evaluate the effective performance of each. Estimates of cost and effectiveness are subsequently compared and the most feasible system selected on the basis of practicality and economy. The process leading to the selection of a feasible alternative consists of the following steps:

- description of alternative means for obtaining protection,
- estimation of cost,
- evaluation of effectiveness,
- comparison
- selection

Depending on the imposed weapon environment, the means of attaining the desired level of protection may be:

evacuation,
shelters in existing structures located by NFSS*,
deliberately designed shelters, or
combinations of these and other available means.

Any synthesis of alternative systems and the consequent evaluation of their effectiveness is only as accurate, complete and consistent as the available data allow. Describing alternate postures for the purpose of achieving selected objectives requires specialized knowledge of means for attaining such. Single- and dual-purpose shelters comprise one segment of feasible means.

For the purposes of selecting and evaluating shelter systems, the necessary data should consist of the following information in readily usable form: Sheltering Options and Survivability Ratings.

* National Fallout Shelter Survey

A "sheltering option" is defined herein to include a shelter structure and any equipment and/or supplies necessary in order to achieve a specified level of protection. It should be described in terms of all pertinent physical characteristics (Appendix A), including costs and anticipated survivability performance relative to imposed weapon environments.

A "survivability rating" (Fig. 1.1) may be described as a mathematical means for representing the protective capability of a given shelter when subjected to a range of weapon environments. Evaluation requires an analysis capable of considering all pertinent weapon effects acting on the shelter and predicting the number of survivors. The need and importance of such ratings is discussed.

Concerning the Need for Personnel Survivability Ratings.--It is customary to design a personnel shelter and rate it (predict its probable performance) based on the weapon environment it is designed to resist. Such designation usually consists of an overpressure level, weapon size and a fallout protection factor (PF). The implication is that for the given environment the shelter is 100 percent effective in providing protection. Such a rating is useful, generally reliable though incomplete. It gives no indication as to shelter performance at higher overpressure levels, different weapon sizes, the effect of multiple attacks, fire resistance, prompt nuclear radiation resistance, etc.

Results of full-scale field tests indicate that this type of rating system is a poor indicator of overall shelter performance. Field tests show that engineered personnel shelters and especially those located below grade, are often 100 percent effective at overpressure levels significantly greater than those they were designed to resist. Some typical results are discussed.

Table 1.1 contains physical characteristics and test results of eight full-scale structures. Each was designed to resist a given overpressure level. Most were tested at overpressure levels significantly greater than the design overpressure level.

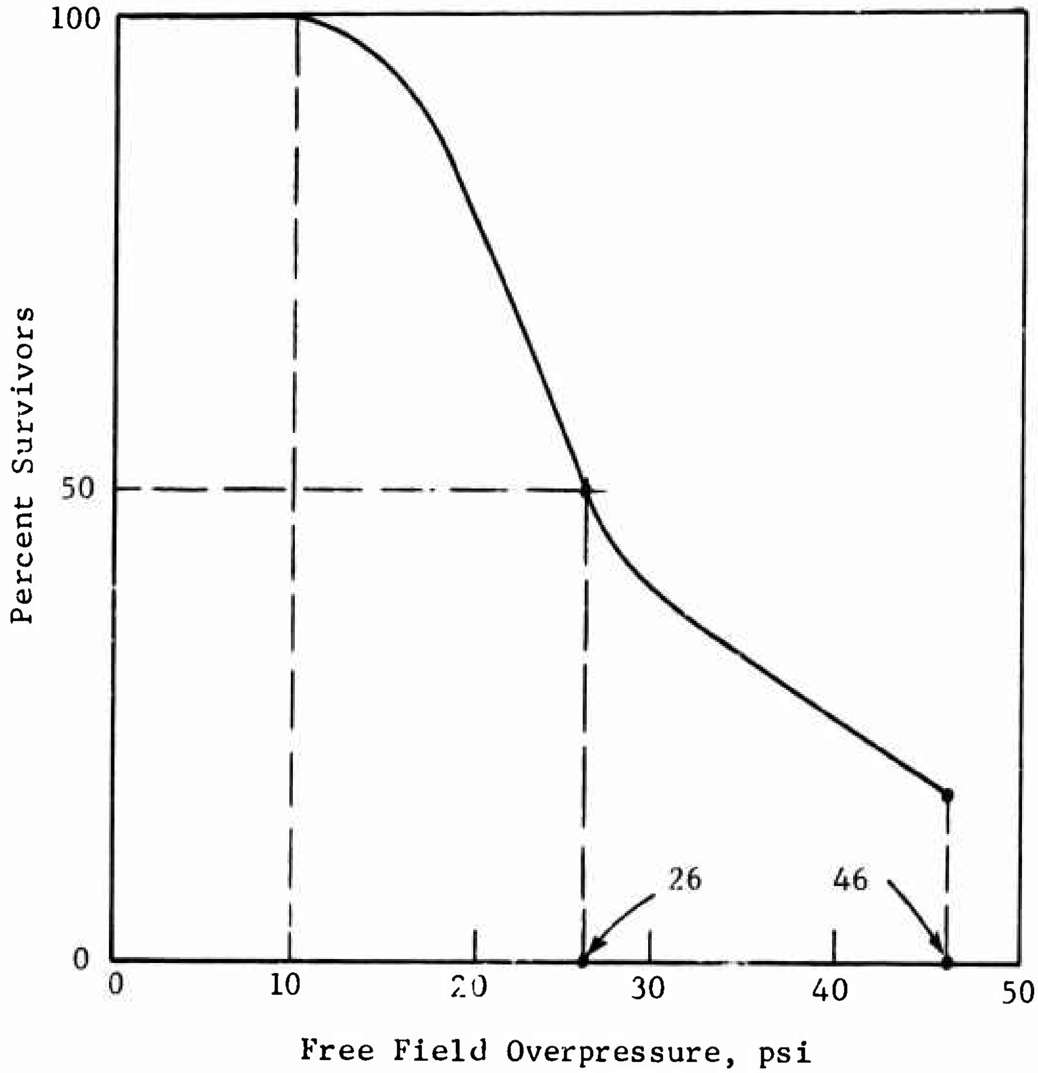



Fig. 1.1 TYPICAL SURVIVABILITY RATING FOR A SHELTER STRUCTURE

TABLE 1.1

SOME DATA ON THE PERFORMANCE OF TEST STRUCTURES

| Category | Structure Designation | Reference | Structural System and Materials of Construction | Design Overpressure (psi) | Anticipated Overpressure at Ground Surface above Structure (psi) | Overpressure Experienced at Ground Surface above Structure (psi) | Level of Structural Damage |
|---|---|---|---|---|---|---|---|
| 1 | 3.3a | 1 | Corrugated Steel Ribbed Arch | > 60 | 75 | 100 | Slight, cracked floor slab, somewhat deformed arch shell. Structures remained serviceable. 100 percent survivors. |
| | 3.3b | 1 | Corrugated Steel Arch | 60 | 50 | 60 | |
| | 3.3c | 1 | Corrugated Steel Ribbed Arch | > 60 | 50 | 60 | |
| 2 | 3.1a | 2 | RC Arches | 50 | 50 | 56 | Slight, cracked shell and floor slab. Structures remained serviceable. 100 percent survivors. |
| | 3.1b | 2 | RC Arches | 50 | 100 | 124 | |
| | 3.1c | 2 | RC Arches | 50 | 200 | 199 | |
| | 3.1n | 2 | RC Arches | 50 | 50 | 56 | |
| 3 | Parking Garage | 2 | RC Rectangular Structure Flat Slab with Column Capitals Construction | 40 | 35 | 39.5 | Slight, cracks at base of column. 100 percent survivors |

Note: The test environment throughout is: weapon size, 36.6 KT; height of burst, 700 ft.

For Category 1, the arch diameter is 25 ft 8 in., arch length is 49 ft, 10 gage corrugated steel is used, the rib size is 6I12.5, the rib spacing is 4 ft, the soil cover is 5 ft and the type of soil is gravely silty sand (density ~115 pcf).

For Category 2, the arch radius is 8 ft, the arch thickness is 8 in., the arch length is 20 ft with the exception of Arch 3.1n which has a length of 32 ft, the main refinforcement is No. 4 @ 10 in., longitudinal reinforcement is No. 4 @ 12 in., soil cover is 4 ft, and the type of soil is gravely silty sand (density ~115 pcf).

All survived the event without appreciable structural damage. It is concluded herein that had these shelters contained shelterees during the event, the shelterees would have survived the effects of blast.

This is admittedly a small sample. It represents eight structures, two structural systems, three materials of construction, several different locations relative to the ground zero, a single weapon size and height of burst. It is nonetheless significant. When other data are considered, such as reported in Refs. 2 through 6, the same conclusion is reached, namely, that a shelter designed to resist a specified overpressure level resulting from a given weapon, will generally be effective at overpressures in excess of the one it was designed to resist.

This conclusion is suggested based on our knowledge of the performance of conventional buildings. Barring earthquakes, tornadoes, floods and other natural disasters, engineered conventional buildings very seldom fail structurally. Building design methods are governed by building codes which are generally based on conservative criteria. The building designer usually spends more time in evaluating functional performance than structural safety. Structural safety is assured by taking a conservative approach and generally at little additional cost.

Knowing that a shelter is 100 percent effective for a given weapon environment is useful, however this information by itself does not give the planner sufficient latitude in planning effective shelter systems. In fact this information alone can lead to shelter systems whose effectiveness and costs are grossly over or underestimated. Consider the following example.

For a 1 MT surface burst, ranges to the 5 and 10 psi free field overpressure contours are shown in Fig. 1.2. Total ground area enclosed by the 5 psi contour is 24.6 sq mi. At 3000 persons/ sq mi (average suburban) this area includes 73,800 persons. Assuming that 5 psi "design rated" shelters are provided, i.e., shelters capable of providing protection up to and including 5 psi overpressure, then all of the people in this area are at risk.

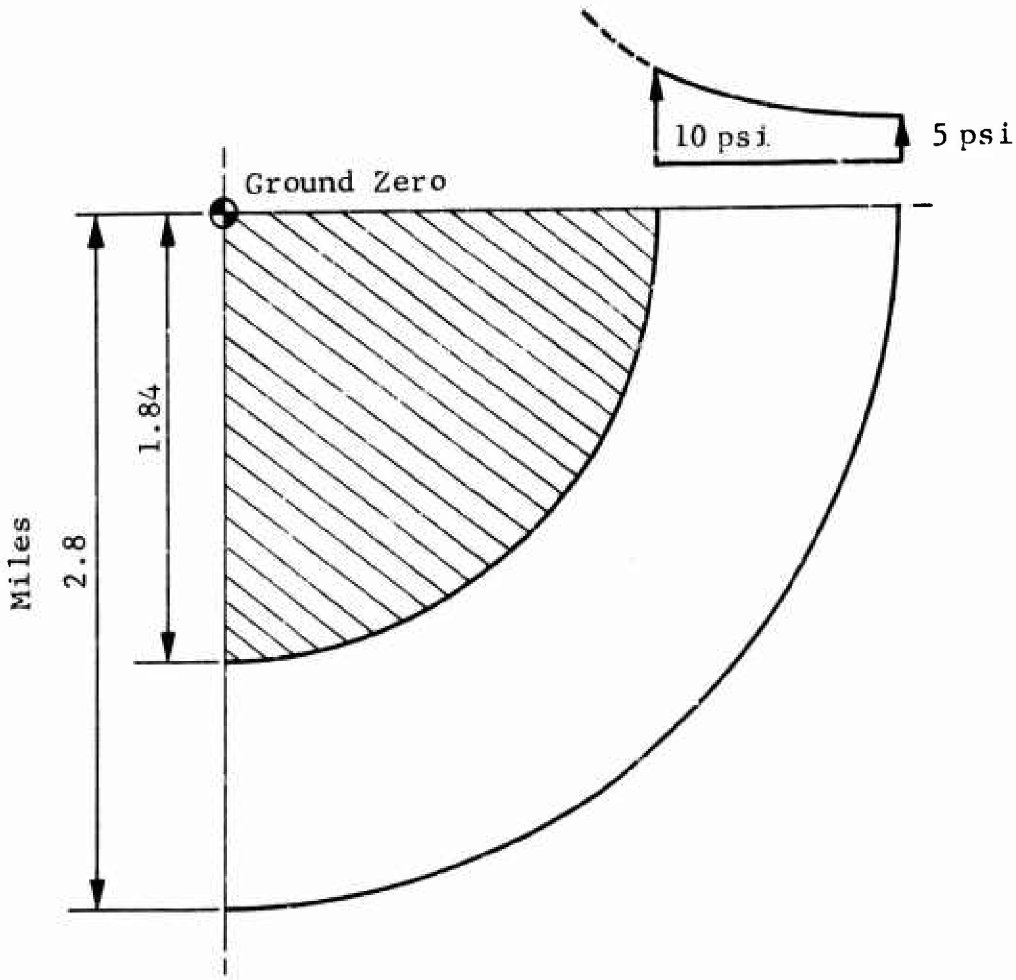



Fig. 1.2 CONSTANT FREE-FIELD OVERPRESSURE CONTOURS FOR A 1 MT SURFACE BURST (5 AND 10 PSI)

If, however, the estimate of shelter design criteria is conservative and protection is maintained to 10 psi, the number of people at risk is 30,300 or 41 percent of the total. This difference is large. Significant degrees of survivability may occur at larger overpressure levels, thus decreasing the effective lethal radius. In terms of overall cost we are actually buying a 10 psi rated system rather than one which is rated at 5 psi. Depending on the type of shelters we are dealing with, a similar argument could also be made in the opposite direction. For reasons given above reliable knowledge of "survivability" of individual shelters is important in the planning of effective shelter systems.

Personnel survivability in deliberate shelters is the subject of this study. Factors associated with its evaluation are discussed.

Evaluation of Survivability.--The level of ability of a personnel shelter in providing protection in a given weapon environment is termed "survivability." Survivability in a given shelter relative to a range of possible weapon environments is represented herein by means of a curve as shown in Fig. 1.1. This is a relationship between a range of overpressure levels and percent survivors. An overpressure level may be related to weapon size, range, height of burst and subsequently to levels of prompt nuclear and thermal radiation. In this hypothetical situation (Fig. 1.1) the shelter is 100 percent effective up to 10 psi. Fifty percent survivors are expected at 26 psi. No information is available beyond 46 psi.

For a given shelter, evaluation of its survivability requires an analysis capable of considering all pertinent weapon effects acting on the shelter and predicting the number of survivors. Central to such an analysis is the accurate description of the weapon environment within the shelter (mechanics) and the corresponding pathogenic (blast biological) response of shelterees.

Shelters treated in this study are restricted to the "especially designed" category and therefore, next to primary and secondary fires and prompt nuclear radiation, blast is the all-important weapon effect. Injury and/or mortality within a shelter may result from these blast-triggered events:

(1) Massive failure of the structure or portions thereof may result in casualties caused by burial or debris.

(2) Pressure and temperature may reach injury levels when doors are not provided or where their capacity is exceeded.

(3) Translation of personnel into a rigid object such as the floor or wall due to interior blast winds or ground shock, and translational interaction of flying debris with people may cause casualties.

(4) Temperature, smoke and toxic gas may build up within the shelter as a result of primary and/or secondary fires in the building housing the shelter.

(5) Fallout radiation may increase due to a decrease in the protection factor resulting from blast damage.

The mechanics portion of realistic estimation of casualties resulting from blast involves fluid dynamics (shelter loading and shelter filling), structural behavior and fire response. Structural behavior plays a key role in each of the injury-producing categories listed. Before we can evaluate casualties resulting from an increase in pressure, interior blast winds, temperature, toxic gases, radiation, etc., we must describe the state of the structure with a reasonable degree of certainty. Shelter system analyses require a definition of shelter effectiveness over a broad range of attack conditions, therefore, we must be able to trace the shelter state from initial yielding to ultimate collapse. Relevant injury producing mechanisms must be identified within this range and their casualty producing protential determined.

The degree to which a shelter is capable of resisting an imposed weapon environment and thus providing protection to personnel within depends on a number of factors which include:

- type of structural system (arch, dome, framed, etc.),
- materials of construction,
- workmanship,
- size,
- location relative to ground surface (buried, semi-buried, at grade, etc.),
- type of soil and foundation conditions,
- type of terrain,
- apertures and closures (size, distribution),
- type and size of building located above the shelter (as in the case of a dual-use basement),
- proximity of shelter to other structures in the area,
- disposition and distribution of personnel within the shelter,
- categories of personnel (old, young, healthy, etc.),
- manner of shock isolation,
- types and quantity of emergency equipment and supplies, etc.

The credibility of an analytically derived survivability rating for any given shelter depends on the extent to which each of these factors are capable of being considered.

Survivability functions for the various shelters considered in this study are presented and discussed in the following section. Costs for several habitability options are included with each shelter. Assumptions employed are briefly discussed below. These are amplified in the various chapters which describe the analysis performed.

In every case, shelter loading is based on the free field blast characteristics given by Brode (Ref. 7). Since in its progress the blast wave is modified by the presence of obstacles such as densely spaced buildings or other terrain features, the free field assumption implies that the subject shelters are located in sparsely populated flat land areas.

Having determined the surface pressure characteristics of the blast wave, the next problem involves the determination of the manner in which the blast pressure is transmitted through the soil and consequently to the shelter. This problem arises on two occasions: (1) when the shelter is fully buried, and (2) when the roof slab is essentially at grade and only the peripheral walls, foundations and floor slabs are in contact with the soil. Rectangular shelters considered belong in the second category in which there is either no soil cover over the roof slab (dual-use basement shelters), or so little cover (single-purpose, rectangular shelters) that soil arching does not occur. The interaction of the peripheral walls with the soil is treated as described in Ref. 8; this is primarily a design approach which is thought to be adequate for the purposes of this study.

With arch shelters properly mounded or fully buried, the configuration of the soil over the arch acts structurally (actively arching) in that it carries a portion of the loading. Design methods for buried arches exist (Refs. 9 and 10), however, when it concerns analysis these are inadequate. The arch-soil interaction problem may be practically approached by means of the finite element method, described in Chapter Two, Vol.II. Even though approximate, this method is more reasonable for purposes of analysis than other available analytic load transfer methods reviewed.

Material properties introduce another level of uncertainty into the overall shelter effectiveness evaluation process. Three types of construction materials are used in the selected shelters: structural steel, reinforced concrete (RC) and soil. The strengths of construction materials often display a substantial spread in data for any one material composition. From the conventional design viewpoint, the low end of the strength spectrum is considered. However, our interest is in the more likely material strength. Consequently, average values of material strength for steel and RC are used.

The question of material properties for soil is less clear-cut. Loads experienced by a buried structure, (magnitude and distribution) depend to a great extent on the nature of the soil surrounding the structure. Unlike material properties for steel, those for soil vary considerably. In this study a single soil is considered for all shelters except the subway station, its properties are described in Chapter Two and correspond to an intermediate stiff clay.

The prediction of failure initiation in the key components of the respective shelters is based on classical small deformation theory, using the blast load characteristics, loading, and material property assumptions described. Where possible, plasticity effects in the soil and structural components are taken into account. Determination of catastrophic failure (postyield behavior) is based on large deflection elasto-plastic analysis, experimental data, and engineering judgment.

It is assumed that positive personal evasive action is taken by all shelter occupants before, during, and after the event. In the first instance it is assumed that shelterees are in preparatory body positions in safe areas of the shelter in anticipation of ground shock and blast filling, i.e., in prone or semiprone positions along main shelter walls and away from entranceways or other possible blast-filling channels.

In the second instance it is assumed that minutes after the event, the shelter and the general surrounding area can be examined for assessment and correction of damage which may produce short and/or long-term hazard to shelterees. This would include freeing of blocked exits and fresh air intake valves, removing of firebrands and combustible debris from critical areas, examining the shelter structure to determine if blast created openings increase fallout radiation hazards and the sealing of such openings where possible, etc.

## 1.1 SURVIVABILITY RATINGS AND COSTS

This section contains survivability ratings and costs of the various shelters considered in the course of this study. The shelters are described in detail in Appendix A, Vol.II, and are outlined below. The results are presented in the same order.

1. Single Purpose Shelters (Low Level Weapon Effects Design)
   A. Reinforced concrete arches (four structures, i.e., fallout radiation design, 10, 20 and 30 psi designs)
   B. Steel arches (four structures; fallout radiation design, 10, 20 and 30 psi designs)
   C. Reinforced concrete rectangular shelters (four structures, i.e., fallout radiation design, 10, 20 and 30 psi designs)
2. Single Purpose Shelters (High Level Weapon Effects Design)

   Reinforced concrete arches (two structures, i.e., 100 and 150 psi designs)
3. Dual-Purpose Shelters
   A. Basement shelters, population 550 persons (three structures, i.e., 5, 25 and 50 psi designs)
   B. Basement shelters, population 1100 persons (three structures, i.e., 5, 25 and 50 psi designs)
   C. Parking garage shelters (three structures, i.e., 5, 25 and 50 psi designs)
   D. Expressway grade separation shelters (three structures, i.e., 5, 25 and 50 psi designs)
   E. Judiciary Square Passenger Station, Washington Metropolitan Subway System (one structure, conventional use design)

Before proceeding with the presentation of results, the meaning of a typical survivability rating is discussed.

A typical survivability rating for a "simple" shelter is shown in Fig. 1.3. It expresses the variation of percent survivors (uninjured or injured shelterees) with free field overpressure for a single weapon attack condition. Injury is defined herein as that level of incapacitation at which the injured is not capable of helping himself.

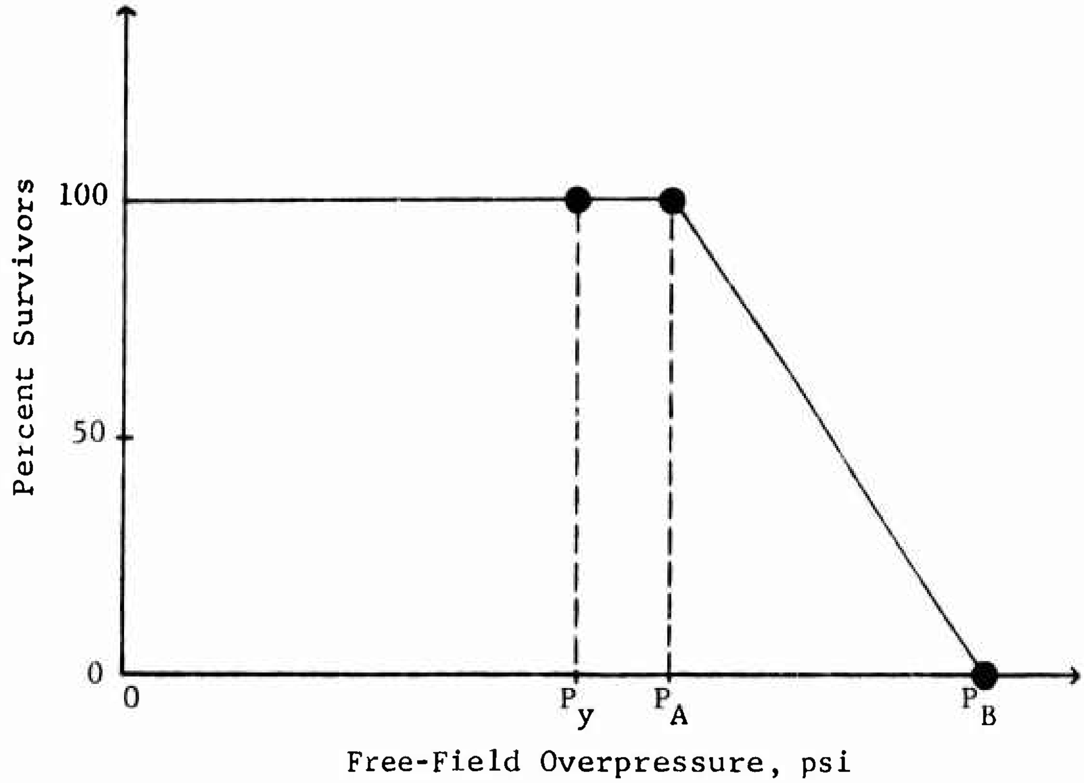



Fig. 1.3 TYPICAL BILINEAR SURVIVABILITY RATING

The survivability rating has a bilinear form and is expressed in terms of two critical free-field overpressure levels, $P_A$ and $P_B$. These levels are first defined in terms of structure response and are subsequently related to survivability. Key points in Fig. 1.3 are described as follows.

Overpressure level $P_y$ designates the point at which the shelter structure begins to yield. At $P_A$ the structure is at the point of incipient failure. It has yielded so that plastic hinges are fully formed in key structural elements, such as a roof slab or an arch shell. Deflections in these components are several times their yield value (see Chapter Two, Vol.II) for specific criteria. It is postulated, however, that these components are still connected and are capable of supporting their own as well as the

initial surcharge dead load. In the conventional sense the structure may be described as "severely damaged." This expression is ordinarily used to describe a large class of damaged structures which may not be easily or economically repaired or rendered capable of some operational function, thus necessitating rebuilding.

Damaged RC slabs which belong within the scope of definition for overpressure level $P_A$ are shown in Figs. 2.8 through 2.10 (Chapter Two, Vol.II). The concrete has cracked and crushed and the reinforcing steel has yielded. However, the steel has not ruptured to any significant degree. It should be noted that during the experiments performed, these slabs were not moved from their supports. Although the concrete has cracked substantially, the vast majority of individual pieces remain attached to the reinforcing steel.

At overpressure level $P_B$ the structure can be described as having experienced "catastrophic collapse." At this point key structural components (roof slabs, arch shells and end walls) are no longer capable of supporting their own weight. With RC roof slabs, the reinforcing steel along yield lines and/or along the periphery ruptures. With arches, in addition to significant distortion (flattening) of the arch shell, the end walls substantially rotate inward about their footings. At this overpressure level the strongest of all key structural components fails in the manner described. The structure no longer exists in a recognizable form.

The definitions given apply equally well to both open as well as closed blast door states in terms of structural response. The reason for this is twofold. For the class of structures considered:

- The primary structural response is rapid compared to the duration of the blast wave; therefore, when doors are missing or open, pressure inside the shelter cannot build up fast enough to significantly reduce the influence of external pressure.

- The size of the shelter opening in relation to the volume of the shelter is such that average pressure-time variations within the shelter, when doors are absent or open, possess significant rise times (about one-half of the positive phase) with peaks considerably less than free-field (see Chapter Four, Vol.II).

It is assumed that internal partitions are not destroyed when blast doors are left off or open.

The definitions of $P_A$ and $P_B$ given earlier apply only to structural response. In the following paragraphs they are related to personnel survivability. The following discussion is centered on the effects of blast pressure loads and ground shock on sheltered personnel.

Referring to Fig. 1.3, in the range of overpressure levels from zero to $P_y$, the structure remains intact. It is subject to motions produced both by blast pressures and ground shock and will deform, but in the elastic range. Structure motions produced by ground shock are transient in nature (several seconds durations) and are characterized by:

- a low-frequency downward displacement which peaks generally near the end of the positive phase, then rebounds and damps out quickly,
- a high frequency acceleration which peaks in the extreme early stages of the motion, and
- a horizontal motion of the structure of similar character.

Depending on the phasing, these motions will couple with those produced by blast pressures. Because of these effects, personnel in prone and sitting positions will experience body vibrations and be subject to collision with the floor as a consequence of the structure dropping out from beneath them or rebounding upward. Impacts may also result from personnel being thrown off balance by motions of the structure as well as blast winds in the event doors are left off or open.

Assuming that shelter equipment is secured and loose objects are grounded, the motions induced in the structure should not produce mortality to sitting and prone shelterees in the range from zero to the $P_y$ overpressure level for the class of shelters studied.

The range from $P_y$ to $P_A$ is somewhat different in terms of the progression of injury producing mechanisms. The structure undergoes increasing distortions with the formation of plastic hinges in key structural components as we approach $P_A$. Since these remain connected and are still self-supporting, the structure remains intact up to the overpressure level $P_A$. Shelterees are subjected to accelerations and displacements, as in the previous range discussed, though to greater injury producing levels. Additional hazard mechanisms are introduced in the case of RC shelters, namely:

- impacts of personnel with pieces of concrete produced by the breakup (large deformation, formation of plastic hinges) in overhead structural members, and
- increases in pressure and temperature within the shelter because of openings in the failed structural components.

For overpressures greater than $P_y$ and less than $P_A$ these additional hazards are not expected to produce fatalities. Experimental data available on the failure of RC slabs indicate that most of the cracked concrete remains attached to the reinforcing steel (see Figs. 2.8 through 2.10, Chapter Two, Vol.II). Pieces that fall off are generally not large, numerous or detached by velocities capable of producing injury or mortality.

Now as far as internal pressures and temperatures are concerned, based on results given in Chapter Four of this study, we predict that cracks and other openings produced in failed key structural components will not result in orifice areas sufficiently large to produce mortality level temperature- or pressure-time pulses inside the shelter.

In the overpressure range discussed ($P_y$ to $P_A$) injuries occur, however since mortality is generally not expected, the survivability curve is a confirmation of the horizontal line from $P_y$ to $P_A$. Mortality begins to occur in the neighborhood of $P_A$, precisely at what point is not known, therefore, the horizontal (100 percent survivors) is extended to $P_A$.

In the range $P_A$ to $P_B$ the hazards are the same as those identified in the previous range, except that they increase in influence as we proceed toward $P_B$; structural motions are greater, structural components may fail catastrophically, etc. As previously defined, at overpressure level $P_B$ the structure experiences catastrophic collapse; the strongest key structural component is no longer capable of supporting its own weight. In the immediate neighborhood of $P_B$ no survivors are expected. The manner in which survivability varies in the range between $P_A$ and $P_B$ is unknown at this time, thus, the two points are connected by a straight line. The straight-line approximation is reasonable for radiation fallout and 10 psi design shelters whose survivability ratings are given in Fig. 1.4. In these two shelter designs, the structure yields, develops plastic hinges, then fails fairly suddenly. The resulting survivability function is similar to a cookie cutter in that the range between $P_A$ and $P_B$ is small. This is not true in the 20 and 30 psi designs shown in Fig. 1.4; here the range from $P_A$ to $P_B$ is greater and the validity for using a straight-line variation is less obvious. However, within the current state-of-the-art, this appears to be the most reasonable assumption.

It is evident that because of differences in workmanship, variation in material properties, etc., seemingly identical shelters behave differently under identical loading conditions. If all of the data required were available, it would be possible to perform a statistical analysis and assign a probability of performance to each survivability rating developed. This was not possible in any rigorous form within the scope of the current study.

At the outset it was stated that for the class of structures considered, the general survivability rating is bilinear in form. Such a representation is accurate when the response of a shelter is governed by the behavior of a single key structural component, as in the case of arch shelters. The protective success of a

simple arch shelter depends primarily on the behavior of the arch shell. This also holds true in the case of a simple, one-room rectangular shelter with the roof slab at grade. In this example effectiveness is governed by the behavior of the roof slab.

If the shelter has several rooms of different sizes, the rating may not be bilinear, instead, its form depends on the relative strengths of the individual roof slabs. For instance, the dual-use shelter basement shown in Fig. 1.9 has a multilinear rating. This shelter has several rooms of different sizes, although the roof slab over each room has the same thickness and percent of reinforcement. The other two shelters described in Fig. 1.9, and those in Fig. 1.8, possess several rooms but the relative strengths of the individual slabs make a bilinear representation of survivability reasonable.

The effects of initial and fallout radiation are not included in the ratings described. Even though the effects of radiation are delayed in time when compared to the effects of blast, radiation nonetheless constitutes a serious hazard. Fallout radiation should not be serious for overpressure levels up to and including $P_A$. In this range the structure is essentially intact and openings produced by the yielding of the structure in the neighborhood of $P_A$ should be mostly in the form of large cracks. Therefore the original PF should not be greatly degraded in this overpressure range. When it concerns prompt nuclear radiation the situation is different in that this can be a serious hazard in the case of low yield weapons. The blast filling problem, i.e., when blast doors are left off or open, is treated in Chapters Three and Five. Survivability functions for this effect are given in Chapter Five.

### 1.1.1 Single-Purpose Shelters (Low Level Weapon Effects Designs)

This category of shelters includes RC arches, steel arches and RC rectangular shelters. Their survivability ratings are given in Fig. 1.4, 1.5 and 1.6 respectively. All of these are simple structures in the sense that their survival is governed primarily by the strength of a single key structural component. In the case of arches the key structural component is the arch shell, in the case of rectangular shelters it is the roof slab. Therefore the bilinear representation of survivability applies reasonably well.

From these results it is evident that methods employed in the actual design of these structures are generally conservative. This fact was brought out in the field tests discusses earlier. Also, a designed single-purpose fallout shelter as such does not exist. Every structure possesses some level of overpressure resistance. The reserve strength depends to a large extent on the structural system materials of construction, location relative to ground surface as well as on the deliberate safety factors employed. The influence of the efficiency of the structural system is evident when we compare the performance of the RC arch to the steel arch and then to the rectangular shelter at any design overpressure level (see Figs. 1.4, 1.5 and 1.6).

Unit costs for this group of shelters is given in Table 1.2 for six different cost options. The cost options are identified in Table 1.3. It should be noted that the survivability functions given apply equally to 500 and 1000 person capacity shelters. A 1000 person capacity shelter is obtained by combining two 500-man shelters. This does not change the basic structural system or its response under the assumptions employed. For this reason the survivability rating does not change. However, in going from a 500-man to a 1000-man shelter the unit cost declines as would be expected.

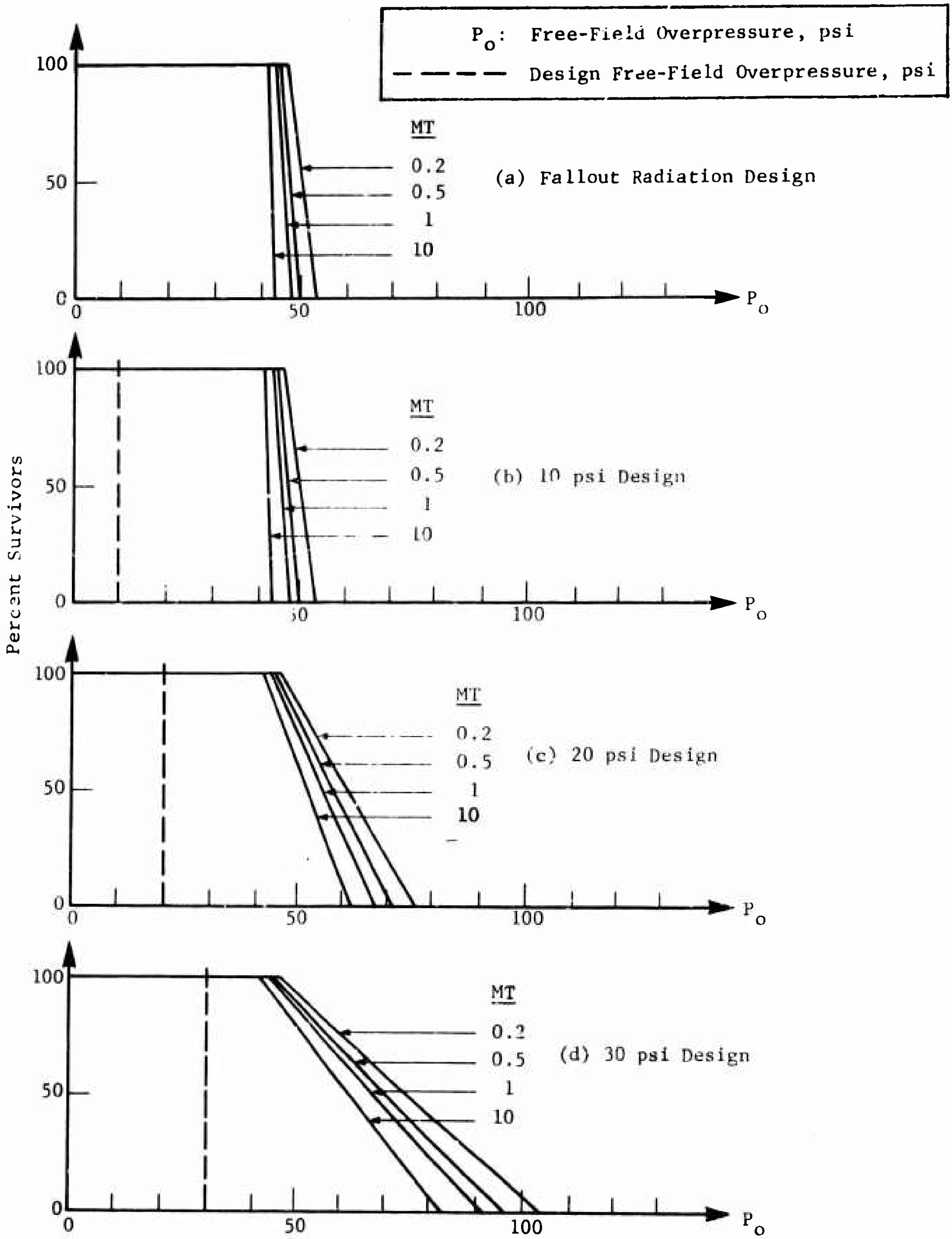



Fig. 1.4 PEOPLE SURVIVABILITY (RC ARCH SHELTERS) (Ref. 14)
LOW LEVEL WEAPON EFFECTS DESIGNS

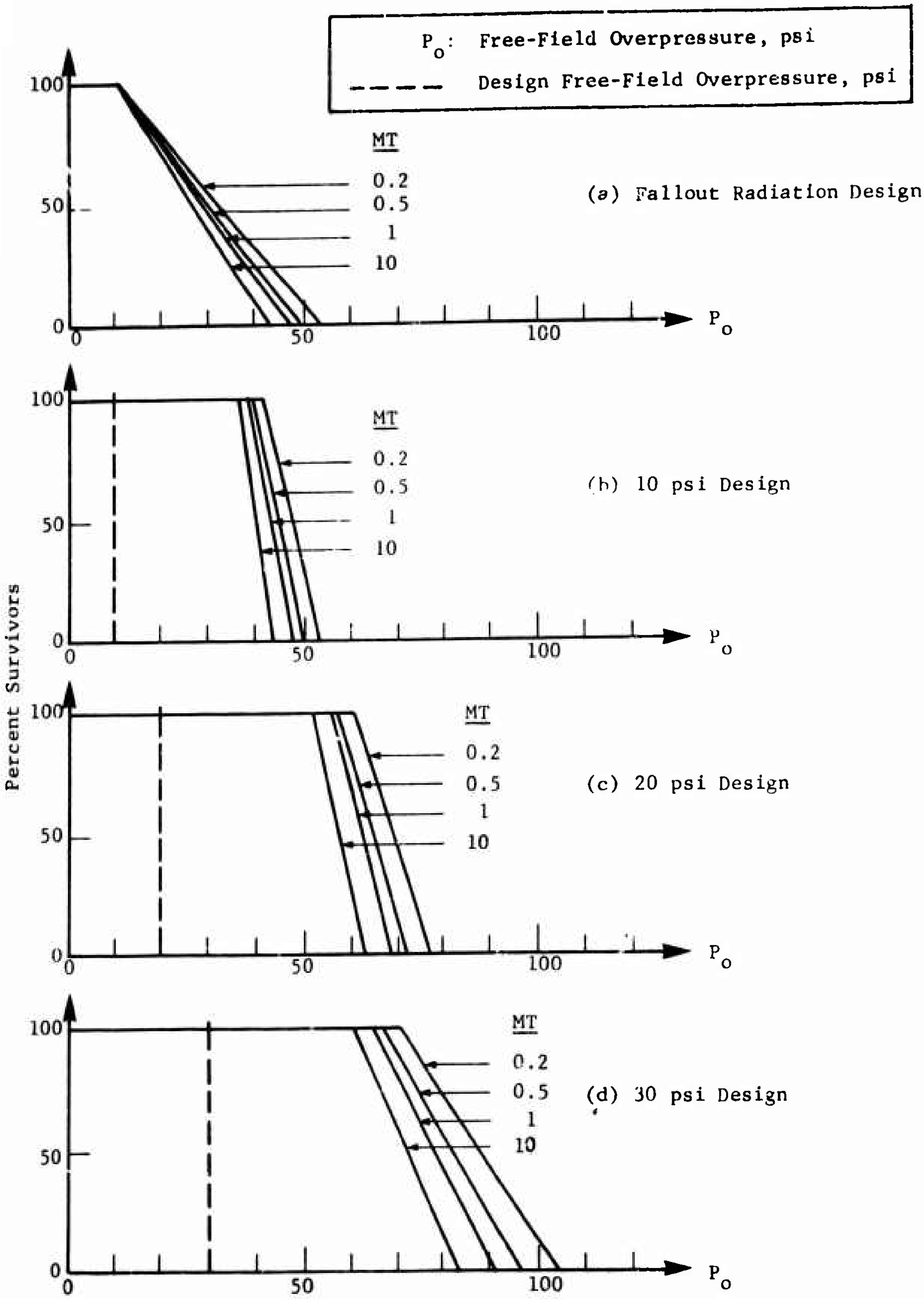



Fig. 1.5 PEOPLE SURVIVABILITY (STEEL ARCH SHELTERS)(Ref. 14)
LOW LEVEL WEAPON EFFECTS DESIGNS

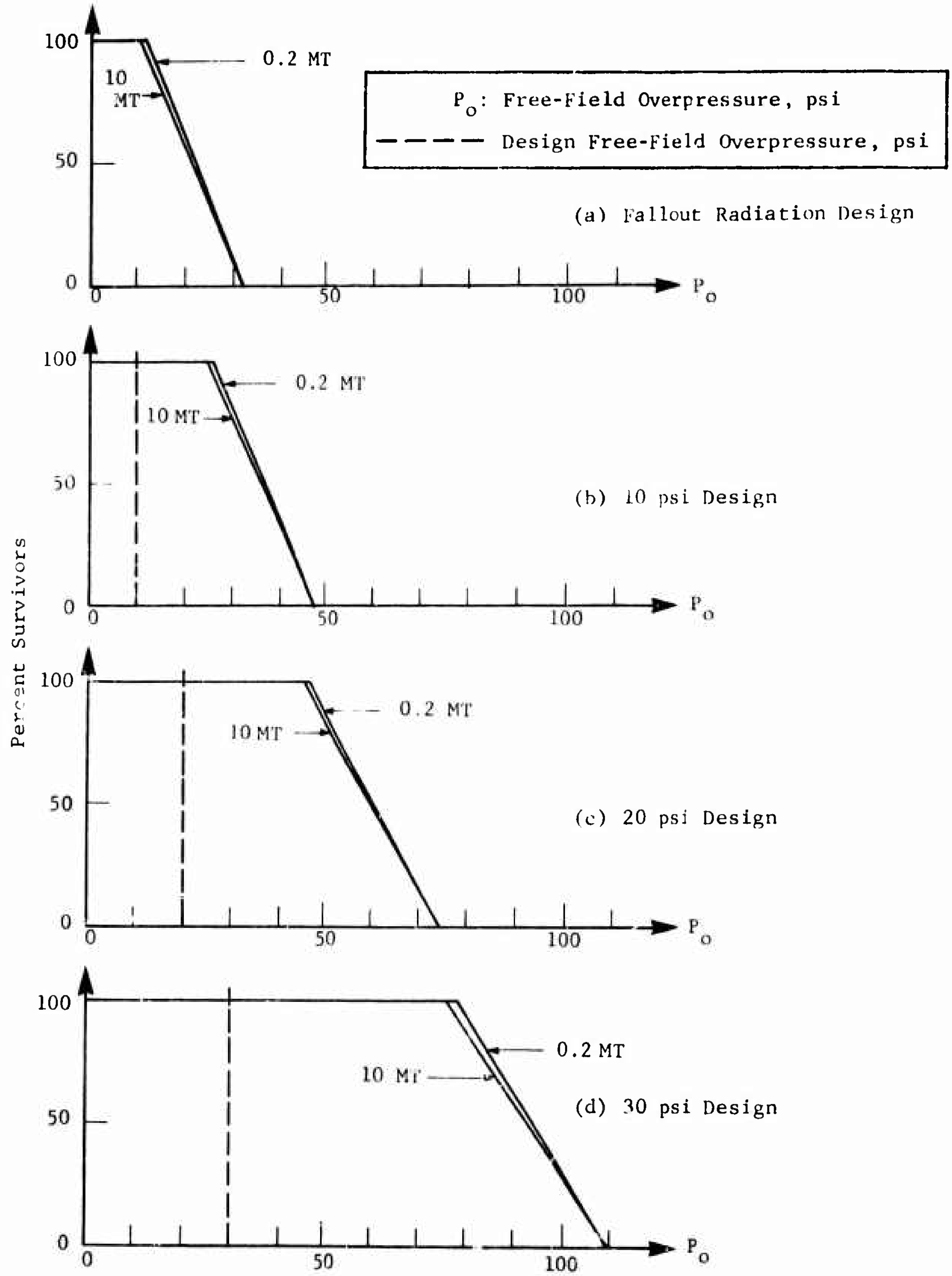



Fig. 1.6 PEOPLE SURVIVABILITY (SINGLE-PURPOSE RC RECTANGULAR SHELTERS) (Ref. 14) LOW LEVEL WEAPON EFFECTS DESIGNS

TABLE 1.2

SUMMARY OF SINGLE-PURPOSE SHELTER COSTS PER SQUARE FOOT OF SHELTER AREA

| Type of Structure | Capacity (No. of Persons) | Cost Option 1 | | | | Cost Option 2 | | | | Cost Option 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Design Weapon Environment | | | | Design Weapon Environment | | | | Design Weapon Environment | | | |
| | | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi |
| R/C Arch | 500 | 10.85 | 11.08 | 11.88 | 12.20 | 11.15 | 11.38 | 12.18 | 12.51 | 15.60 | 15.83 | 16.63 | 16.95 |
| | 1000 | 10.30 | 10.56 | 11.07 | 11.65 | 10.61 | 10.86 | 11.38 | 11.95 | 15.05 | 15.31 | 15.83 | 16.40 |
| Steel Arch | 500 | 10.16 | 11.85 | 13.57 | 19.34 | 10.46 | 12.16 | 13.88 | 19.64 | 14.91 | 16.61 | 18.32 | 24.09 |
| | 1000 | 9.51 | 11.59 | 13.31 | 19.06 | 9.82 | 11.89 | 13.62 | 19.36 | 14.27 | 16.34 | 18.06 | 23.81 |
| R/C Rectangular | 500 | 10.93 | 12.94 | 15.12 | 19.14 | 11.20 | 12.11 | 15.40 | 19.41 | 15.21 | 17.22 | 19.41 | 23.42 |
| | 1000 | 9.76 | 11.74 | 13.77 | 17.40 | 10.03 | 12.01 | 14.05 | 17.68 | 14.04 | 16.02 | 18.06 | 21.69 |
| | | Cost Option 4 | | | | Cost Option 5 | | | | Cost Option 6 | | | |
| | | Design Weapon Environment | | | | Design Weapon Environment | | | | Design Weapon Environment | | | |
| | | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi | FRE | 10 psi | 20 psi | 30 psi |
| R/C Arch | 500 | 17.83 | 18.06 | 18.87 | 19.19 | 18.14 | 18.37 | 19.17 | 19.49 | 22.59 | 22.81 | 23.62 | 23.94 |
| | 1000 | 17.54 | 17.80 | 18.32 | 18.89 | 17.85 | 18.10 | 18.62 | 19.20 | 22.30 | 22.50 | 23.07 | 23.64 |
| Steel Arch | 500 | 17.17 | 18.84 | 20.56 | 26.33 | 17.45 | 19.14 | 20.86 | 26.63 | 21.90 | 23.59 | 25.31 | 31.08 |
| | 1000 | 16.76 | 18.83 | 20.55 | 26.30 | 17.06 | 19.13 | 20.86 | 26.60 | 21.51 | 23.58 | 25.31 | 31.05 |
| R/C Rectangular | 500 | 18.44 | 20.45 | 22.64 | 26.65 | 18.71 | 20.72 | 22.91 | 26.92 | 22.72 | 24.73 | 26.92 | 30.93 |
| | 1000 | 15.67 | 17.65 | 19.69 | 23.31 | 15.94 | 17.92 | 19.96 | 23.59 | 19.95 | 21.93 | 23.97 | 27.60 |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

TABLE 1.3

SHELTERING COST OPTIONS FOR SINGLE-PURPOSE SHELTERS

(Cost Items Comprising Sheltering Options Considered)

| Cost Option | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| Site Clearance | Site Clearance | Site Clearance | Same as Option 1 | Same as Option 2 | Same as Option 3 |
| Access Road | Access Road | Access Road | | | |
| Shelter Structure | Shelter Structure | Shelter Structure | | | |
| Entranceway | Entranceway | Entranceway | | | |
| — | OCD Ventilation Package | Ventilation System* | | | |
| — | OCD Water Package | Water Supply System* Toilet System* | | | |
| — | OCD Electrical | Wiring, Fixtures and Outlets* | | | |
| — | — | Partitions | | | |
| — | — | — | Parking Lot | Parking Lot | Parking Lot |

*commercial items

Note: A detailed breakdown of costs for these items is given in Appendix B, Vol.II.

### 1.1.2 Single-Purpose Shelters (High Level Weapon Effects Designs)

Survivability ratings of two RC arches having a 500-man capacity each are discussed herein. One was designed to resist 100 psi free-field overpressure and associated effects of prompt nuclear and fallout radiation, the other was designed to resist 150 psi. The structural configuration and the basic layout dimensions are identical to the RC arch shelters described in the previous subsection. The basic difference is in the entranceways. While corrugated steel entranceways were used in the previous designs, the entranceways for this set of shelters consist of RC, which was found to be more practical for the high design overpressures considered.

Survivability ratings for the two shelters are given in Fig. 1.7. By the definition given earlier, these are simple structures and a bilinear representation of survivability is reasonable. The ratings given reflect survivability potentials against the external blast effects.

Unit costs for six cost options are given in Table 1.4. The cost options are identified in Table 1.3.

TABLE 1.4

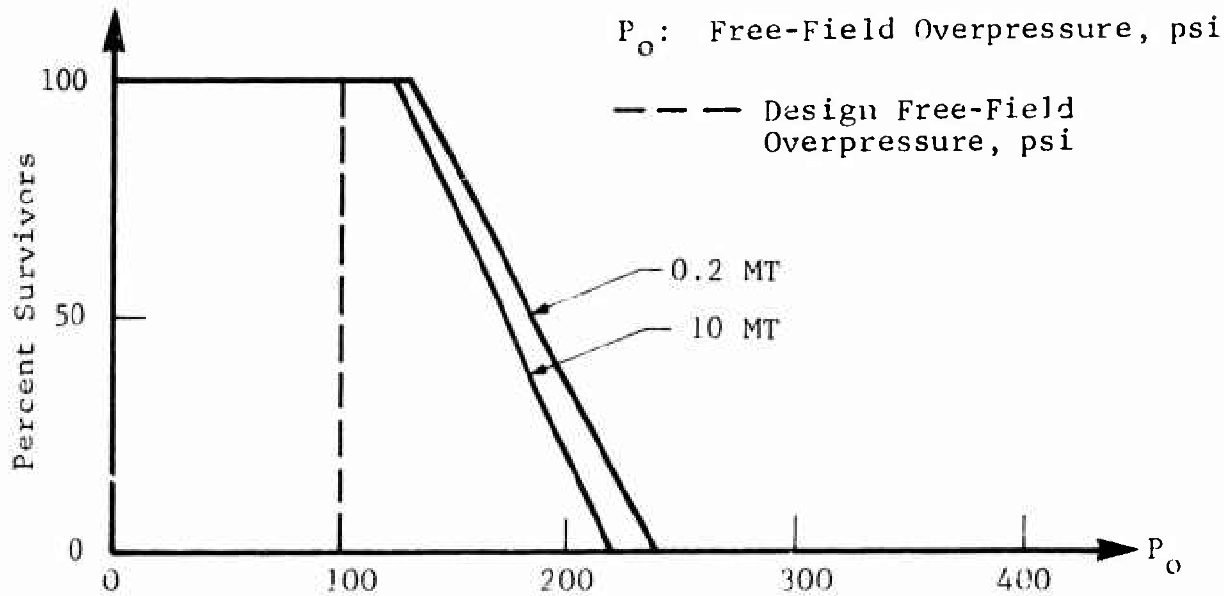
SUMMARY OF SINGLE-PURPOSE SHELTER COSTS PER SQUARE FOOT OF SHELTER AREA

| Design Weapon Environment | Cost Option | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 100 psi | 17.06 | 17.33 | 22.78 | 25.45 | 25.71 | 31.15 |
| 150 psi | 21.69 | 21.95 | 27.39 | 30.07 | 30.34 | 35.57 |

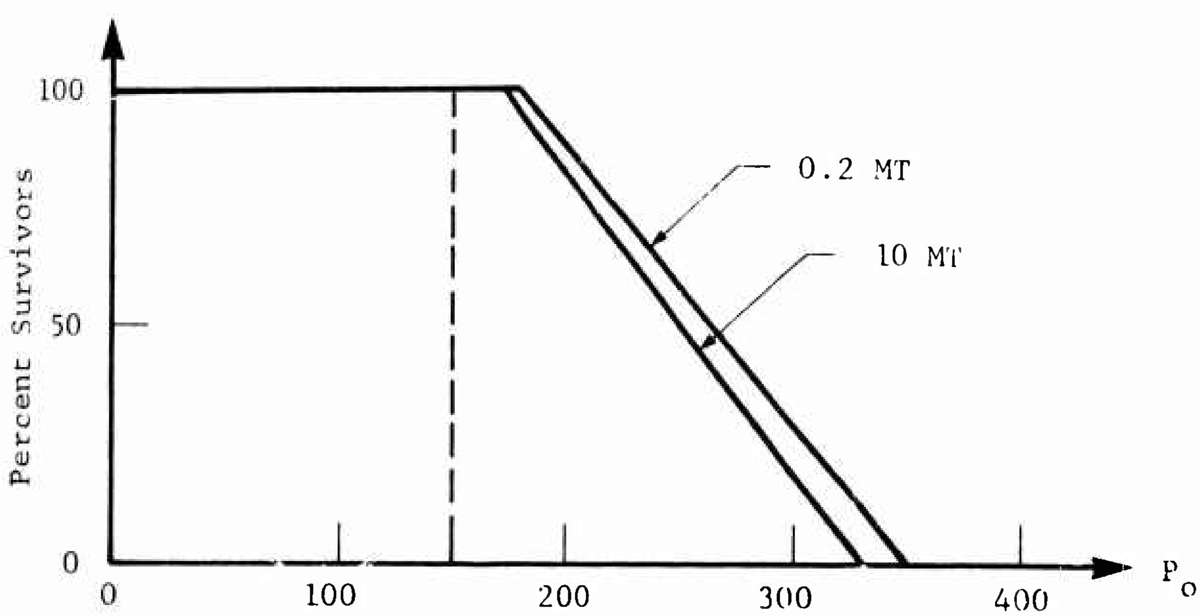
Costs given are valid for suburban areas of Chicago, Illinois for spring 1969.

### 1.1.3 Dual-Purpose Shelters

School Basement and Parking Garage Shelters.--School basements whose survivability ratings are given herein are described in Appendix A, Vol.II. Both are one-level structures whose roof slabs are at grade. A brief description of both is given.




(a) 100 psi Design




(b) 150 psi Design

Fig. 1.7 PEOPLE SURVIVABILITY (HIGH LEVEL WEAPON EFFECTS DESIGNS)

Two school basements (Ref. 15) ordinarily used as classrooms, were (slanted) designed to act as shelters in the event of an emergency. Both schools are modern two-story structures consisting of a steel frame, filler walls and having large areas of window space. The first school accommodates 550 persons, the second 1100 persons. Basement shelter designs for 5, 25 and 50 psi overpressure levels and associated effects resulting from megaton range nuclear weapons were analyzed. Resulting survivability ratings are given in Figs. 1.8 and 1.9.

As in previous cases the designs are conservative as reflected by the overpressure level at which yielding of the structure begins. These structures are sufficiently "simple" such that under the assumptions employed, a bilinear representation of survivability is reasonable for most cases studied.

Unit incremental costs for these structures are given in Tables 1.5, 1.6, and 1.7. Three cost options were considered and are identified in Table 1.8.

Parking garage shelters (Ref. 16) were designed (slanted) to serve the dual function of parking garage during normal operation and shelter during emergency. Two types are considered; Structure I is designed to be located below a parking lot, Structure II is designed to be located below a city park (see Appendix A, Vol. II). The roof slab in both cases consists of a flat slab spanning between the peripheral walls and interior columns. Designs for 5, 25 and 50 psi overpressure levels resulting from megaton range nuclear weapons were analyzed. Resulting survivability ratings are given in Fig. 1.10. As compared to previous results the designs of these shelters are not as conservative. Adequate steel and concrete could have been provided even though flat slabs are not as amenable to slanting as one- and two-way slabs due to the punching action at the columns. Survivability ratings given apply to Structure I as well as to Structure II.

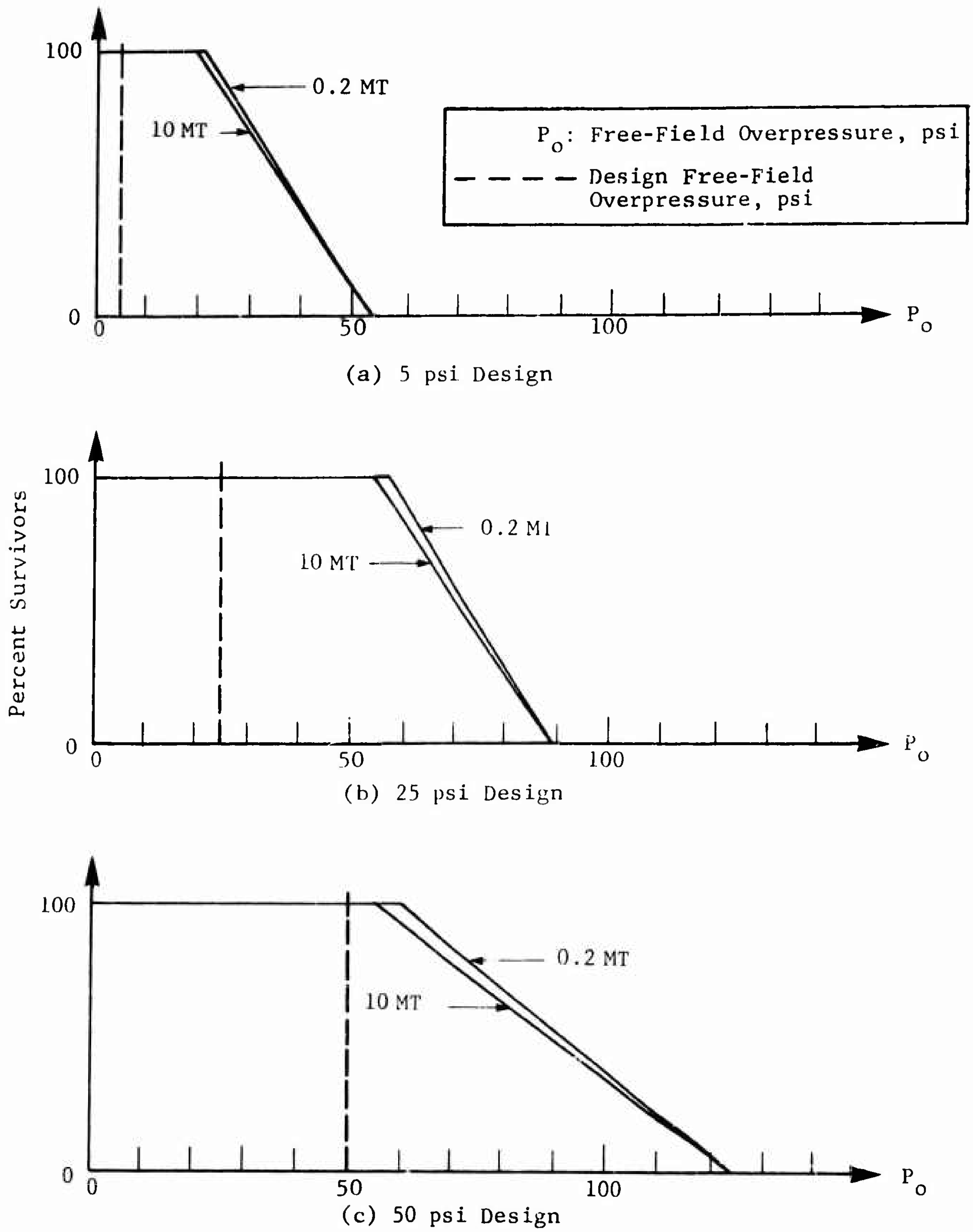



Fig. 1.8 PEOPLE SURVIVABILITY (DUAL-USE BASEMENT SHELTERS, POPULATION 550 PERSONS)(Ref. 15)

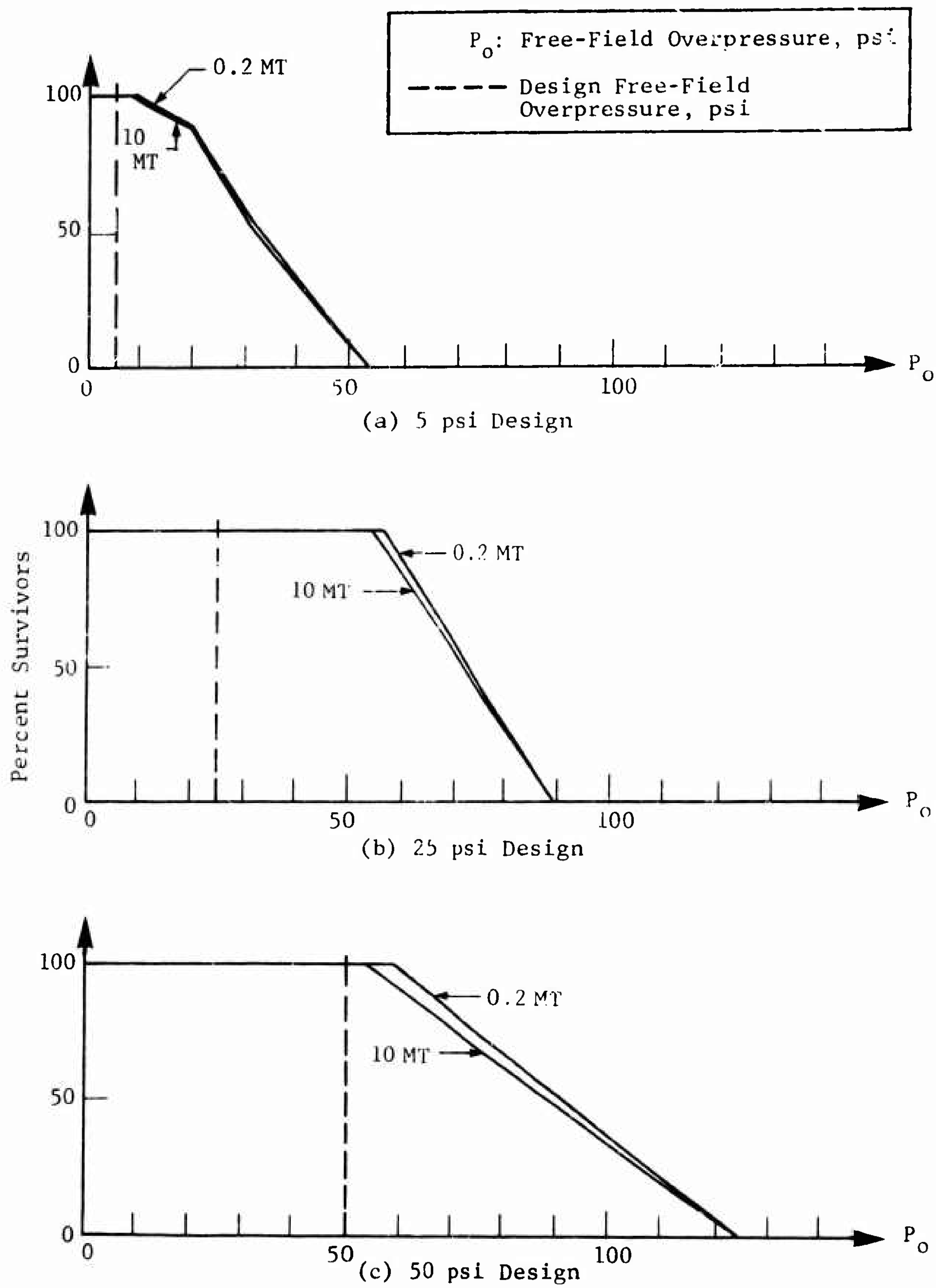



Fig. 1.9 PEOPLE SURVIVABILITY (DUAL-USE BASEMENT SHELTERS, POPULATION 1100 PERSONS) (Ref. 15)

TABLE 1.5

SUMMARY OF TOTAL COSTS FOR SCHOOL BASEMENT SHELTERS, COST OPTION 1

| Capacity | Description | Conventional | | Design Weapon Environment, psi | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5 | | 25 | | 50 | |
| | | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) |
| Population 550 Gross Floor Area 6440 sq ft | Earthwork and Structural | 45,748 | 41.9 | 50,596 | 44.3 | 70,902 | 52.5 | 95,770 | 58.1 |
| | Architectural | 12,260 | 11.2 | 11,594 | 10.2 | 8,594 | 6.4 | 8,594 | 5.2 |
| | Mechanical | 21,027 | 19.2 | 21,027 | 18.3 | 21,027 | 15.5 | 21,027 | 12.7 |
| | Electrical | 11,948 | 11.0 | 11,948 | 10.5 | 11,948 | 8.9 | 11,948 | 7.3 |
| | Total Direct Contract Cost | 90,983 | -- | 95,165 | -- | 112,471 | -- | 137,339 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 18,197 | 16.7 | 19,033 | 16.7 | 22,494 | 16.7 | 27,468 | 16.7 |
| | Total Cost | 109,180 | 100.0 | 114,198 | 100.0 | 134,965 | 100.0 | 164,807 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | | -- | | -- | | -- |
| | Unit Cost (total) | 16.95 | -- | 17.73 | -- | 20.96 | -- | 25.59 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.78 | -- | 4.01 | -- | 8.64 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 4.6% | -- | 23.6% | -- | 51.0% | -- |
| Population 1100 Gross Floor Area 12,260 sq ft | Earthwork and Structural | 81,788 | 41.6 | 87,057 | 43.0 | 122,804 | 51.5 | 166,604 | 57.2 |
| | Architectural | 21,138 | 10.7 | 20,675 | 10.2 | 15,025 | 6.3 | 15,025 | 5.2 |
| | Mechanical | 38,313 | 19.5 | 38,313 | 18.9 | 38,313 | 16.0 | 38,313 | 13.1 |
| | Electrical | 22,680 | 11.5 | 22,680 | 11.2 | 22,680 | 9.5 | 22,680 | 7.8 |
| | Total Direct Contract Cost | 163,919 | -- | 168,725 | -- | 198,822 | -- | 242,622 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 32,784 | 16.7 | 33,745 | 16.7 | 39,764 | 16.7 | 48,524 | 16.7 |
| | Total Cost | 196,703 | 100.0 | 202,470 | 100.0 | 238,586 | 100.0 | 291,146 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 5,767 | -- | 41,883 | -- | 94,443 | -- |
| | Unit Cost (total) | 16.04 | -- | 16.51 | -- | 19.46 | -- | 23.75 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.47 | -- | 3.42 | -- | 7.71 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 2.9% | -- | 21.3% | -- | 48.0% | -- |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

## TABLE 1.6

SUMMARY OF TOTAL COSTS FOR SCHOOL BASEMENT SHELTERS, COST OPTION 2

| Capacity | Description | Conventional | | Design Weapon Environment, psi | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5 | | 25 | | 50 | |
| | | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) |
| Population 550 Gross Floor Area 6440 sq ft | Earthwork and Structural | 45,748 | 41.9 | 50.596 | 43.7 | 70,902 | 51.9 | 95.770 | 57.6 |
| | Architectural | 12,260 | 11.2 | 11,594 | 10.0 | 8,594 | 6.3 | 8,594 | 5.2 |
| | Mechanical | 21,027 | 19.2 | 22,039 | 19.0 | 22,039 | 16.1 | 22,039 | 13.2 |
| | Electrical | 11,948 | 11.0 | 12,223 | 10.6 | 12,223 | 9.0 | 12,223 | 7.3 |
| | Total Direct Contract Cost | 90,983 | -- | 96,452 | -- | 113,758 | -- | 138,626 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 18,197 | 16.7 | 19,290 | 16.7 | 22,752 | 16.7 | 27,725 | 16.7 |
| | Total Cost | 109,180 | 100.0 | 115,742 | 100.0 | 136,510 | 100.0 | 166,351 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 6,562 | -- | 27,330 | -- | 57,171 | -- |
| | Unit Cost (total) | 16.95 | -- | 17.97 | -- | 21.20 | -- | 25.83 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 1.02 | -- | 4.25 | -- | 8.88 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 6.0% | -- | 25.1% | -- | 52.39% | -- |
| Population 1100 Gross Floor Area 12,260 sq ft | Earthwork and Structural | 81,788 | 41.6 | 87,057 | 42.4 | 122,804 | 50.8 | 166,604 | 56.6 |
| | Architectural | 21,138 | 10.7 | 20,675 | 10.0 | 15,025 | 6.2 | 15,025 | 5.1 |
| | Mechanical | 38,313 | 19.5 | 40,337 | 19.6 | 40,337 | 16.7 | 40,337 | 13.7 |
| | Electrical | 22,680 | 11.5 | 23,230 | 11.3 | 23,230 | 9.6 | 23,230 | 7.9 |
| | Total Direct Contract Cost | 163,919 | -- | 171,299 | -- | 201,396 | -- | 245,196 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 32,784 | 16.7 | 34,260 | 16.7 | 40,279 | 16.7 | 49,039 | 16.7 |
| | Total Cost | 196,793 | 100.0 | 205,559 | 100.0 | 241,675 | 100.0 | 294,235 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 8,856 | -- | 44,972 | -- | 97,532 | -- |
| | Unit Cost (total) | 16.04 | -- | 16.77 | -- | 19.71 | -- | 24.00 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.73 | -- | 3.67 | -- | 7.96 | -- |
| | Cost Difference Over Conventional (%) | -- | -- | 4.6% | -- | 22.8% | -- | 49.6% | -- |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

TABLE 1.7
SUMMARY OF TOTAL COSTS FOR SCHOOL BASEMENT SHELTERS, COST OPTION 3

| Capacity | Description | Conventional | | Design Weapon Environment, psi | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5 | | 25 | | 50 | |
| | | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) |
| Population 550<br>Gross Floor Area 6440 sq ft | Earthwork and Structural | 45,748 | 41.9 | 50,596 | 42.5 | 70,902 | 50.0 | 95,770 | 55.8 |
| | Architectural | 12,260 | 11.2 | 11,594 | 9.7 | 8,594 | 6.1 | 8,594 | 5.0 |
| | Mechanical | 21,027 | 19.2 | 21,330 | 17.9 | 22,187 | 15.6 | 22,187 | 12.9 |
| | Electrical | 11,948 | 11.0 | 15,755 | 13.2 | 16.538 | 11.6 | 16,538 | 9.6 |
| | Total Direct Contract Cost | 90,983 | -- | 99,275 | -- | 118,221 | -- | 143,089 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 18,197 | 16.7 | 19,855 | 16.7 | 23,644 | 16.7 | 28,618 | 16.7 |
| | Total Cost | 109,180 | 100.0 | 119,130 | 100.0 | 141,865 | 100.0 | 171,707 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 9,950 | -- | 32,685 | - | 62,527 | -- |
| | Unit Cost (total) | 16.95 | -- | 18.50 | -- | 22.03 | -- | 26.67 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 1.55 | -- | 5.08 | -- | 9.72 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 9.1% | -- | 30.0% | -- | 57.4% | -- |
| Population 1100<br>Gross Floor Area 12,260 sq ft | Earthwork and Structural | 81,788 | 41.6 | 87,057 | 41.5 | 122,804 | 49.5 | 166,604 | 55.3 |
| | Architectural | 21,138 | 10.7 | 20,675 | 9.9 | 15,025 | 6.0 | 15,025 | 5.0 |
| | Mechanical | 38,313 | 19.5 | 38,678 | 18.4 | 39,799 | 16.0 | 39,799 | 13.2 |
| | Electrical | 22,680 | 11.5 | 28,350 | 13.5 | 29,430 | 11.8 | 29,430 | 9.8 |
| | Total Direct Contract Cost | 163,919 | -- | 174,760 | -- | 207,058 | -- | 250,858 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 32,784 | 16.7 | 34,952 | 16.7 | 41,412 | 16.7 | 50,172 | 16.7 |
| | Total Cost | 196,703 | 100.0 | 209,712 | 100.0 | 248,470 | 100.0 | 301,030 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 13,009 | -- | 41,767 | -- | 104,327 | -- |
| | Unit Cost (total) | 16.04 | -- | 17.11 | -- | 20.27 | -- | 24.55 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 1.07 | -- | 4.23 | -- | 8.51 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 6.7% | -- | 26.4% | -- | 53.0% | |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

TABLE 1.8

SHELTERING COST OPTIONS (DUAL-USE SHELTERS)

<u>Cost Option 1</u>

(1) Shelter structure, conventional doors, blast doors, stairs and associated hardware

(2) Mechanical and electrical equipment of commercial variety commensurate with conventional use only. Special mechanical and electrical equipment capable of reliable functioning under emergency conditions is not provided.

<u>Cost Option 2</u>

(1) Shelter structure, conventional doors, blast doors, stairs and associated hardware

(2) Mechanical and electrical equipment of commercial variety commensurate with conventional use only

(3) Recommended OCD items:

- ventilation kits
- water containers convertible to chemical toilets
- electrical package

<u>Cost Option 3</u>

(1) Shelter structure, conventional doors, blast doors, stairs and associated hardware

(2) Mechanical and electrical equipment of commercial variety commensurate with conventional as well as emergency use

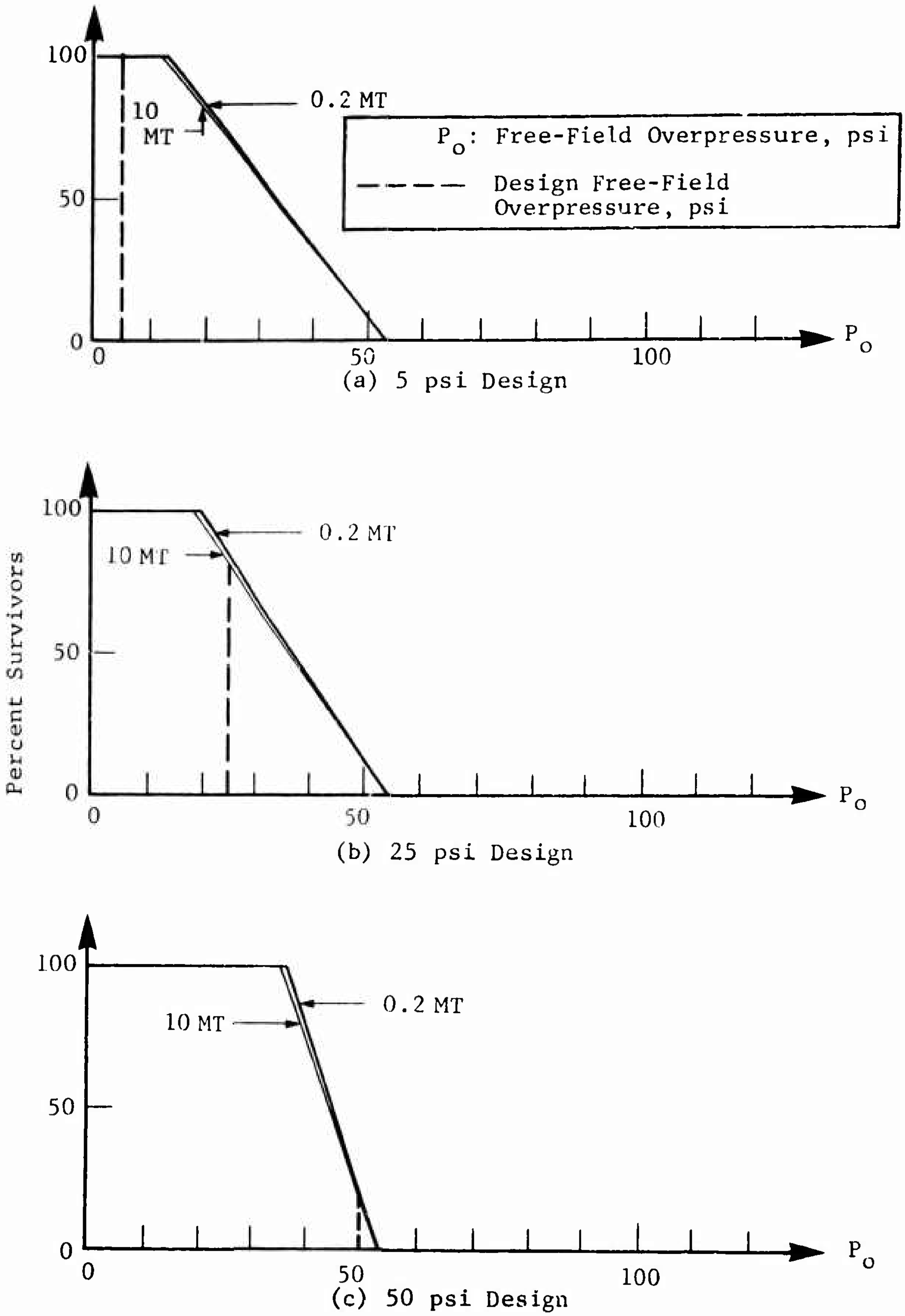



Fig. 1.10 PEOPLE SURVIVABILITY (PARKING GARAGE SHELTERS STRUCTURES I AND II)(Ref. 16)

Both structures are identical except that the first was designed to support a street load parking lot while the second, which would be located below a city park was designed to support 3 ft of soil. The difference is in cost. The second structure requires more excavation and therefore more backfill.

Unit incremental costs are given in Table 1.9 and 1.10. Three cost options were considered and are identified in Table 1.8.

1.1.4 Expressway Grade Separation Shelters

Expressway grade separation shelters considered in this study belong in the dual-use category. Their physical characteristics, advantages, shortcoming and costs are described in Appendix A, Vol.II. The purpose of this section is to describe their sheltering potential.

Shelters considered are illustrated in Figs. 1.11, 1.12 and 1.13. These illustrations provide basic plans for three shelters each designed to resist a different "design overpressure" level, i.e., 5, 25 and 50 psi. Figure 1.11 shows a three-dimensional, cutaway view of one side of the grade separation (bridge) modified to include a personnel shelter. The shelter has two levels. The upper level plan is given in Fig. 1.12 and the lower level plan in Fig. 1.13. This is a RC structure which makes use of the conventional, structural portions of the bridge. Its interior and exterior walls carry vertical loads and are designed to act as shear walls and to resist flexure.

From the structural analysis point of view this shelter concept is considerably more complex than any of the shelters described thus far. The increased complexity is due to the following conditions. The shelter is partially above and partially below grade. It has two levels and a significant number of internal, load resisting partitions. It is an integral part of a bridge. Its response is dependent on the direction from which the blast wave arrives. Due to these complexities the corresponding survivability function is not expected to be of the simple bilinear form obtained earlier.

# TABLE 1.9

SUMMARY OF TOTAL COSTS FOR PARKING GARAGE SHELTERS, STRUCTURE I, FOR VARIOUS COST OPTIONS
(Capacity 5000 Persons, Gross Floor Area 51,670 sq ft)

| Cost Option | Description | Conventional | | Design Weapon Environments, psi | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 5 | | 25 | | 50 | |
| | | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) |
| 3 | Earthwork and Structural | 309,602 | 56.2 | 328,412 | 55.4 | 501,976 | 62.1 | 712,236 | 67.2 |
| | Architectural | 42,670 | 7.7 | 42,303 | 7.1 | 40,770 | 5.0 | 40,770 | 3.8 |
| | Mechanical | 83,511 | 15.2 | 88,480 | 14.9 | 93,940 | 11.6 | 93,940 | 8.9 |
| | Electrical | 23,126 | 4.2 | 34,706 | 5.9 | 36,918 | 4.6 | 36,918 | 3.4 |
| | Total Direct Contract Cost | 458,909 | -- | 493,901 | -- | 673,604 | -- | 883,864 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 91,782 | 16.7 | 98,780 | 16.7 | 134,721 | 16.7 | 176,773 | 16.7 |
| | Total Cost | 550,691 | 100.0 | 592,681 | 100.0 | 808,325 | 100.0 | 1,060,637 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 41,990 | -- | 257,634 | -- | 509,946 | -- |
| | Unit Cost (total) | 10.66 | -- | 11.47 | -- | 15.64 | -- | 20.53 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.81 | -- | 4.98 | -- | 9.87 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 7.6% | -- | 46.7% | -- | 92.7% | -- |
| 1 | Earthwork and Structural | 309,602 | 56.2 | 328,412 | 57.3 | 501,976 | 64.4 | 712,236 | 69.0 |
| | Architectural | 42,670 | 7.7 | 42,303 | 7.4 | 40,770 | 5.2 | 40,770 | 4.0 |
| | Mechanical | 83,511 | 15.2 | 83,511 | 14.6 | 83,511 | 10.7 | 83,511 | 8.1 |
| | Electrical | 23,126 | 4.2 | 23,126 | 4.0 | 23,126 | 3.0 | 23,126 | 2.2 |
| | Total Direct Contract Cost | 458,909 | -- | 477,352 | -- | 649,383 | -- | 859,643 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 91,782 | 16.7 | 95,470 | 16.7 | 129,877 | 16.7 | 171,929 | 16.7 |
| | Total Cost | 550,691 | 100.0 | 572,822 | 100.0 | 779,260 | 100.0 | 1,031,572 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 22,131 | -- | 228,569 | -- | 480,881 | -- |
| | Unit Cost (total) | 10.66 | -- | 11.09 | -- | 15.08 | -- | 19.96 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.43 | -- | 4.42 | -- | 9.30 | -- |
| | Cost Difference Over Conventional (%) | -- | -- | 4.0% | -- | 41.5% | -- | 87.2% | -- |
| 2 | Earthwork and Structural | 309,602 | 56.2 | 328,412 | 56.0 | 501,976 | 63.3 | 712,236 | 68.1 |
| | Architectural | 42,670 | 7.7 | 42,303 | 7.2 | 40,770 | 5.2 | 40,770 | 3.8 |
| | Mechanical | 83,511 | 15.2 | 92,711 | 15.8 | 92,711 | 11.7 | 92,711 | 8.9 |
| | Electrical | 23,126 | 4.2 | 25,626 | 4.3 | 25,626 | 3.1 | 25,626 | 2.5 |
| | Total Direct Contract Cost | 458,909 | -- | 489,052 | -- | 661,083 | -- | 871,343 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 91,782 | 16.7 | 97,810 | 16.7 | 132,217 | 16.7 | 174,269 | 16.7 |
| | Total Cost | 550,691 | 100.0 | 586,862 | 100.0 | 793,300 | 100.0 | 1,045,612 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 36,171 | -- | 242,609 | -- | 494,921 | -- |
| | Unit Cost (total) | 10.66 | -- | 11.36 | -- | 15.35 | -- | 20.23 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.70 | -- | 4.69 | -- | 9.57 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 6.6% | -- | 44.0% | -- | 89.8% | -- |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

## TABLE 1.10

SUMMARY OF TOTAL COSTS FOR PARKING GARAGE SHELTERS, STRUCTURE II, FOR VARIOUS COST OPTIONS
(Capacity 5000 Persons, Gross Floor Area 51,670 sq ft)

| Cost Option | Description | Conventional | | Design Weapon Environments, psi: 5 | | 25 | | 50 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) | Cost ($) | Total Cost (%) |
| 3 | Earthwork and Structural | 395,101 | 61.7 | 408,288 | 60.9 | 545,476 | 64.5 | 752,392 | 68.8 |
| | Architectural | 31,480 | 4.9 | 27,648 | 4.1 | 28,290 | 3.3 | 28,290 | 2.6 |
| | Mechanical | 83,511 | 13.1 | 88,480 | 13.2 | 93,940 | 11.1 | 93,940 | 8.6 |
| | Electrical | 23,126 | 3.6 | 34,706 | 5.1 | 36,918 | 4.4 | 36,918 | 3.3 |
| | Total Direct Contract Cost | 533,218 | -- | 559,122 | -- | 704,624 | -- | 911,540 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 106,644 | 16.7 | 111,824 | 16.7 | 140,925 | 16.7 | 182,308 | 16.7 |
| | Total Cost | 639,862 | 100.0 | 670,946 | 100.0 | 845,549 | 100.0 | 1,093,848 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 31,084 | -- | 205,687 | -- | 453,986 | -- |
| | Unit Cost (total) | 12.38 | -- | 12.99 | -- | 16.36 | -- | 21.17 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.61 | -- | 3.98 | -- | 8.79 | -- |
| | Cost Increase Over Conventional (%) | -- | -- | 4.9% | -- | 32.1% | -- | 71.0% | -- |
| 1 | Earthwork and Structural | 395,101 | 61.7 | 408,288 | 62.7 | 545,476 | 66.8 | 752,392 | 70.7 |
| | Architectural | 31,480 | 4.9 | 27,648 | 4.2 | 28,290 | 3.5 | 28,290 | 2.6 |
| | Mechanical | 83,511 | 13.1 | 83,511 | 12.8 | 83,511 | 10.2 | 83,511 | 7.8 |
| | Electrical | 23,126 | 3.6 | 23,126 | 3.6 | 23,126 | 2.8 | 23,126 | 2.2 |
| | Total Direct Contract Cost | 533,218 | -- | 542,573 | -- | 680,403 | -- | 887,319 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 106,644 | 16.7 | 108,515 | 16.7 | 136,081 | 16.7 | 177,464 | 16.7 |
| | Total Cost | 639,862 | 100.0 | 651,088 | 100.0 | 816,484 | 100.0 | 1,064,783 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 11.226 | -- | 176,622 | -- | 424,921 | -- |
| | Unit Cost (total) | 12.38 | -- | 12.60 | -- | 15.80 | -- | 20.61 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.22 | -- | 3.42 | -- | 8.23 | -- |
| | Cost Difference Over Conventional (%) | -- | -- | 1.8% | -- | 27.6% | -- | 66.5% | -- |
| 2 | Earthwork and Structural | 395,101 | 61.7 | 408,288 | 61.4 | 545,476 | 65.7 | 752,392 | 69.7 |
| | Architectural | 31,480 | 4.9 | 27,648 | 4.2 | 28,290 | 3.3 | 28,290 | 2.6 |
| | Mechanical | 83,511 | 13.1 | 92,711 | 13.9 | 92,711 | 11.2 | 92,711 | 8.6 |
| | Electrical | 28.126 | 3.6 | 25,626 | 3.8 | 25,626 | 3.1 | 25,626 | 2.4 |
| | Total Direct Contract Cost | 533,218 | -- | 554,273 | -- | 692,103 | -- | 899,019 | -- |
| | Contractor's Profit and Overhead Contingencies (20%) | 106,644 | 16.7 | 110,855 | 16.7 | 138,421 | 16.7 | 179,804 | 16.7 |
| | Total Cost | 639,862 | 100.0 | 665,128 | 100.0 | 830,524 | 100.0 | 1,078,823 | 100.0 |
| | Cost Difference Over Conventional | -- | -- | 25,266 | -- | 190,662 | -- | 438,961 | -- |
| | Unit Cost (total) | 12.38 | -- | 12.87 | -- | 16.07 | -- | 20.88 | -- |
| | Unit Cost Difference Over Conventional | -- | -- | 0.49 | -- | 3.69 | -- | 8.50 | -- |
| | Cost Difference Over Conventional (%) | -- | -- | 4.0% | -- | 29.8% | -- | 68.7% | -- |

Costs given are valid for suburban areas of Chicago, Illinois for the spring of 1969.

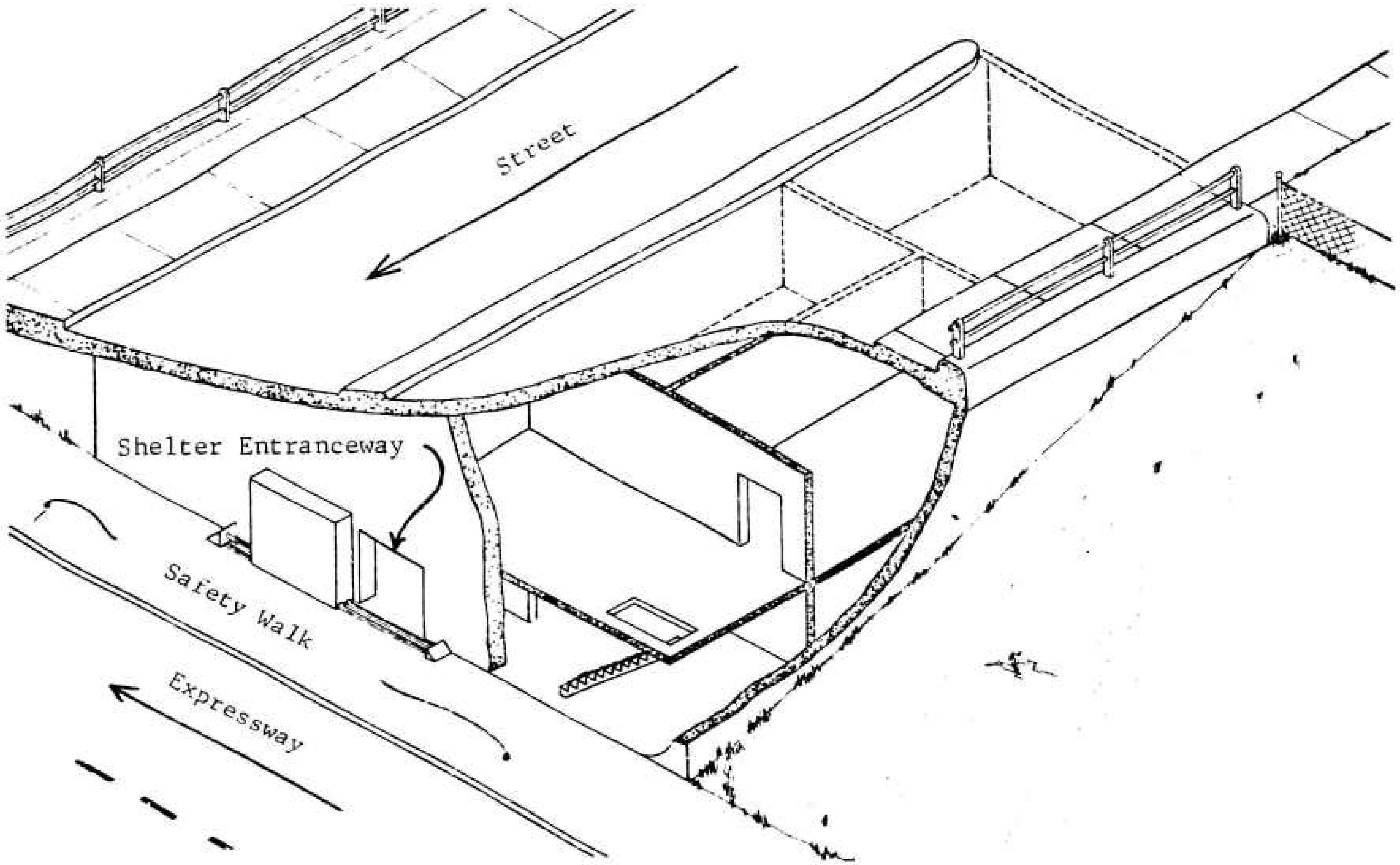



Fig. 1.11 CUTAWAY VIEW OF AN EXPRESSWAY GRADE SEPARATION SHELTER

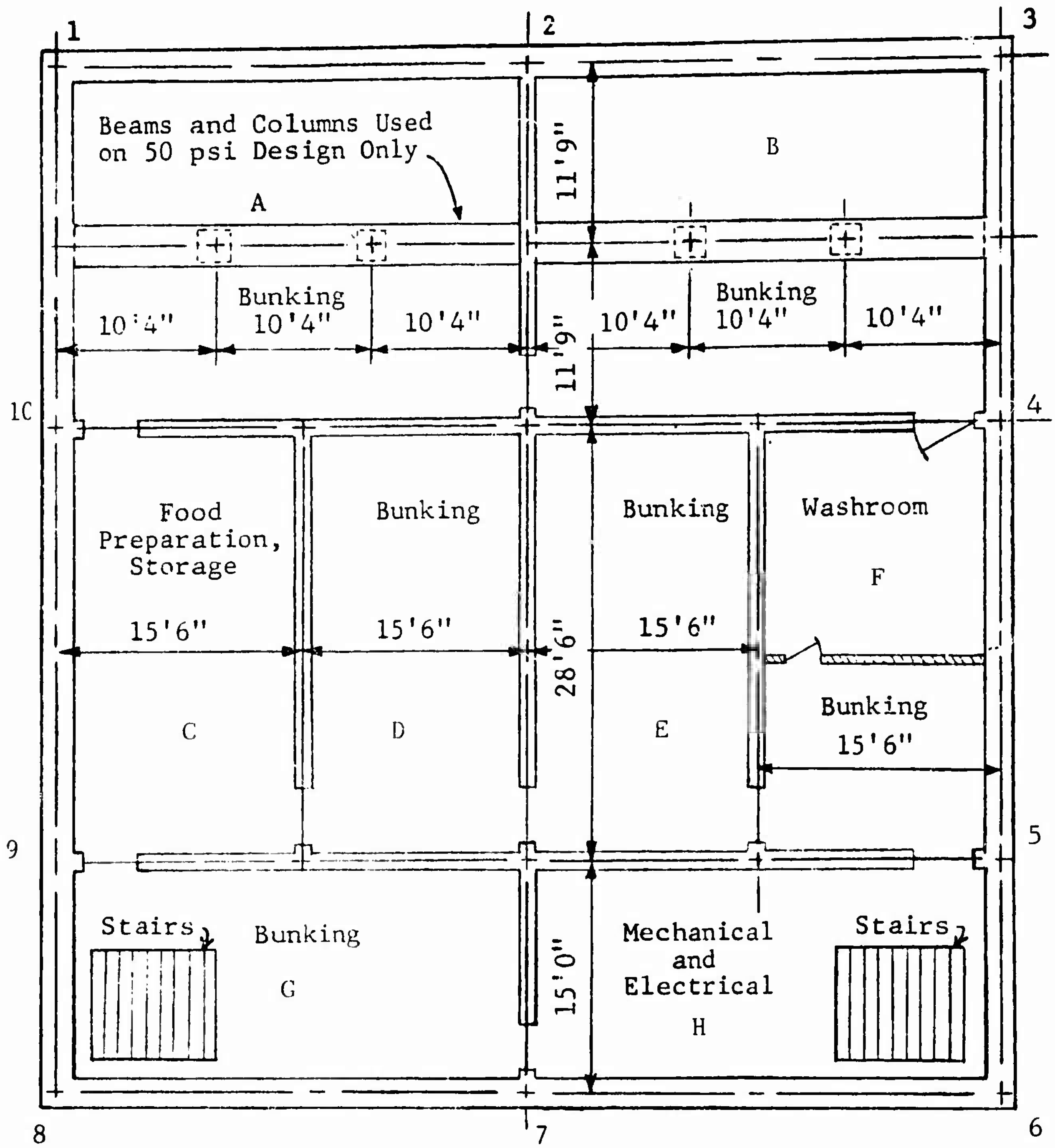



Fig. 1.12 UPPER LEVEL FLOOR PLAN

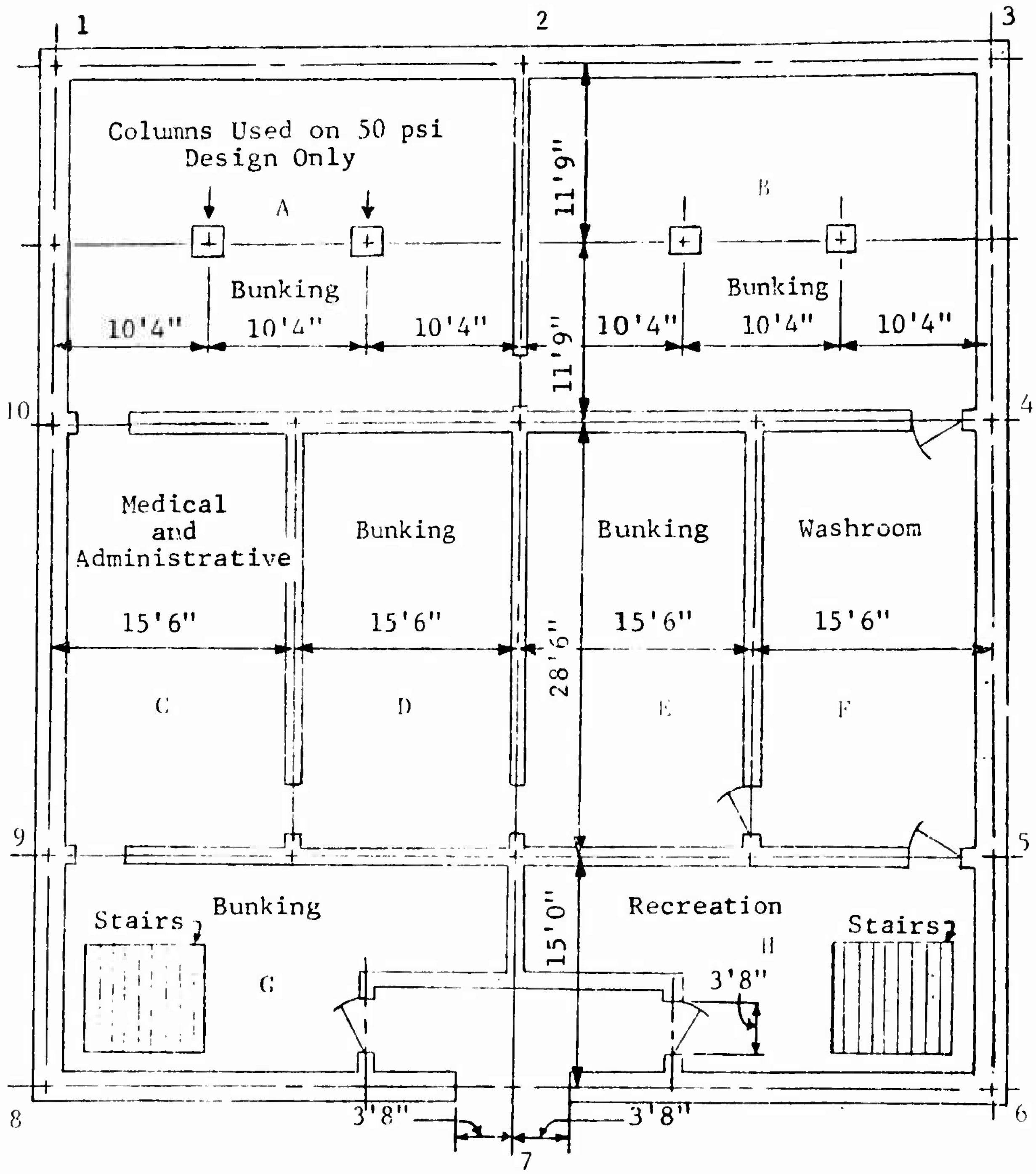



Fig. 1.13 LOWER LEVEL FLOOR PLAN

The analytic approach taken is the same as described in Section 2.1 of this report. Incipient and catastrophic failure overpressures were determined for each peripheral structural element on an individual basis. These values are given in Table 1.11 for each of the three shelters. Loading condition assumptions are explained in Fig. 1.14.

Failure overpressures for individual structural elements were used to determine corresponding failure overpressures for individual rooms. The results are given in Tables 1.12, 1.13 and 1.14. In these tables individual rooms are identified as shown in Fig. 1.12 and 1.13. The number of people that would be located in each of these rooms is also indicated. It is assumed that room H (upper level) would be unoccupied since it contains electrical and mechanical equipment. A room is considered to have failed (incipient or catastrophic) if any of its walls or its ceiling has failed.

Room failure overpressures given in Tables 1.12, 1.13 and 1.14 were used in the subsequent step to construct survivability tables, i.e., number of survivors in each room. This was done by constructing a bilinear survivability function (see Fig. 1.3) for each individual room and on this basis estimating the number of survivors for a range of overpressure levels. Results obtained are given in Tables 1.15 through 1.20. These tables were constructed on the assumption that the interior walls and the intermediate level slab are infinitely strong and are thus not capable of failing.

Survivability functions are plotted in Fig. 1.15. The upper curve represents results given in Tables 1.15 through 1.20. The lower represents the assumption that catastrophic failure of the entire structure occurs at failure of its weakest part. The true survivability curve, for injury and mortality produced by structural collapse, will lie between these bounding curves.

TABLE 1.11

INCIPIENT AND CATASTROPHIC FAILURE OVERPRESSURES FOR INDIVIDUAL SHELTER COMPONENTS (PSI)

| Component | | Incipient Failure Overpressure | | | Catastrophic Failure Overpressure | | |
|---|---|---|---|---|---|---|---|
| | Design Overpressure | 5 | 25 | 50 | 5 | 25 | 50 |
| Roof | A | 38 | 60 | 61 | 73 | 90 | 112 |
| | B | 38 | 60 | 61 | 73 | 90 | 112 |
| | C | 62 | 62 | 78 | 87 | 87 | 114 |
| | D | 62 | 62 | 78 | 87 | 87 | 114 |
| | E | 62 | 62 | 78 | 87 | 87 | 114 |
| | F | 62 | 62 | 78 | 87 | 87 | 114 |
| | G | 46 | 46 | 55 | 85 | 85 | 115 |
| | H | 46 | 46 | 55 | 85 | 85 | 115 |
| Lower Level | 1-2 | 65 | 109 | 138 | 88 | 111 | 173 |
| | 2-3 | 65 | 109 | 138 | 88 | 111 | 173 |
| | 3-4 | 146 | 146 | 182 | 329 | 329 | 533 |
| | 4-5 | 140 | 140 | 175 | 576 | 576 | 936 |
| | 5-6 | 157 | 157 | 196 | 323 | 323 | 523 |
| | 6-7 | 69 | 69 | 86 | 150 | 150 | 348 |
| | 7-8 | 69 | 69 | 86 | 150 | 150 | 238 |
| | 8-9 | 157 | 157 | 196 | 323 | 323 | 523 |
| | 9-10 | 140 | 140 | 175 | 576 | 576 | 936 |
| | 10-1 | 146 | 146 | 182 | 329 | 329 | 523 |

| Component | | Incipient Failure Overpressure | | | Catastrophic Failure Overpressure | | |
|---|---|---|---|---|---|---|---|
| | Design Overpressure | 5 | 25 | 50 | 5 | 25 | 50 |
| Upper Level | 1-2 | 65 | 109 | 138 | 88 | 111 | 173 |
| | 2-3 | 65 | 109 | 138 | 88 | 111 | 173 |
| | 3-4F* | 61 | 61 | 72 | 146 | 146 | 185 |
| | 3-4S** | 69 | 69 | 86 | 152 | 152 | 240 |
| | 4-5F | 50 | 50 | 56 | 178 | 178 | 248 |
| | 4-5S | 68 | 68 | 85 | 263 | 263 | 425 |
| | 5-6F | 61 | 61 | 71 | 145 | 145 | 183 |
| | 5-6S | 69 | 69 | 86 | 152 | 152 | 239 |
| | 6-7F | 59 | 59 | 69 | 144 | 144 | 180 |
| | 6-7S | 69 | 69 | 86 | 150 | 150 | 238 |
| | 7-8F | 59 | 59 | 69 | 144 | 144 | 180 |
| | 7-8S | 69 | 69 | 86 | 150 | 150 | 238 |
| | 8-9F | 61 | 61 | 71 | 145 | 145 | 183 |
| | 8-9S | 69 | 69 | 86 | 152 | 152 | 239 |
| | 9-10F | 50 | 50 | 56 | 178 | 178 | 248 |
| | 9-10S | 68 | 68 | 85 | 263 | 263 | 425 |
| | 10-1F | 61 | 61 | 72 | 146 | 146 | 185 |
| | 10-1S | 69 | 69 | 86 | 152 | 152 | 240 |

*F; Face-on loading condition

**S; Side-on loading condition

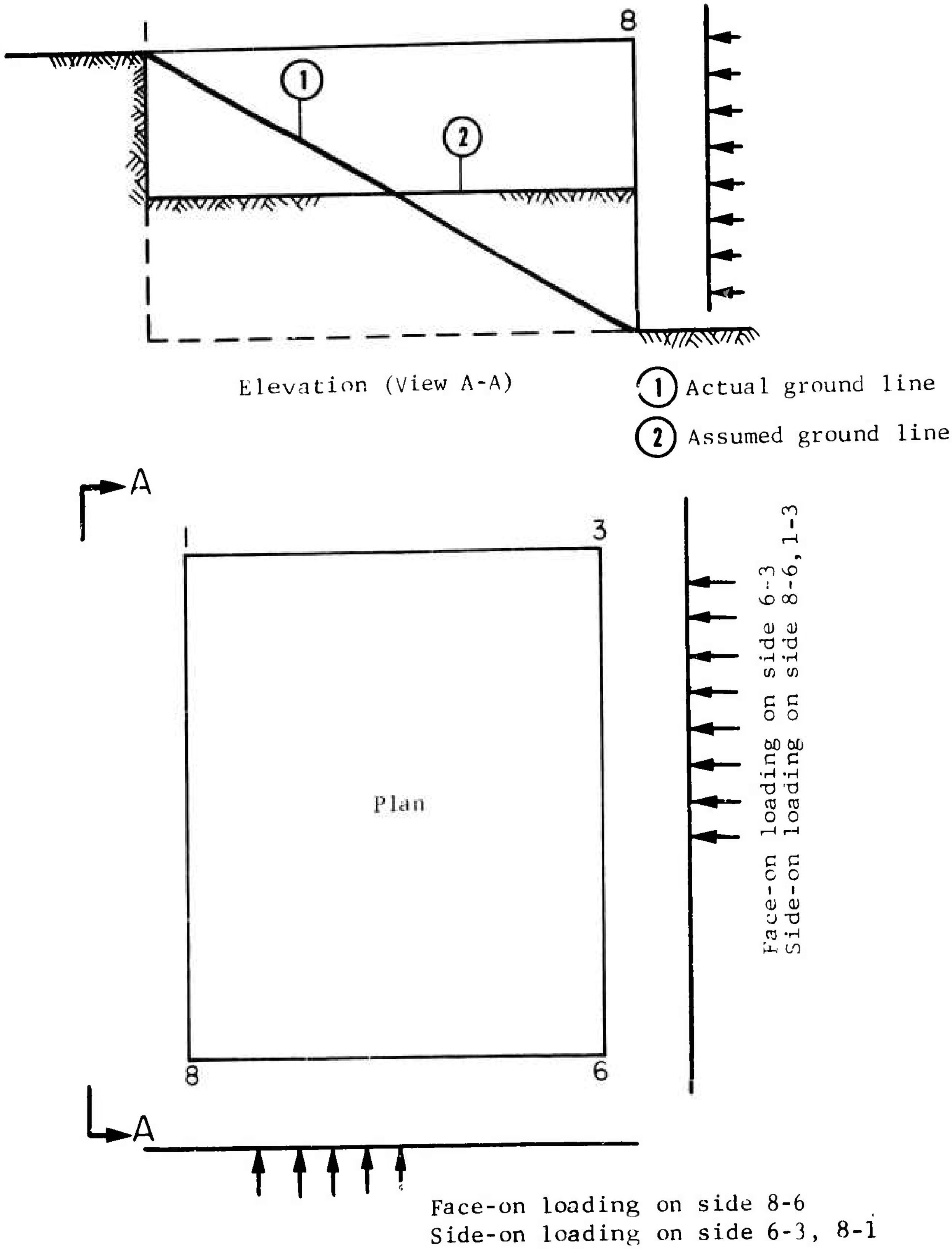



Fig. 1.14 SHELTER LOADING ASSUMPTIONS

TABLE 1.12

ROOM FAILURE OVERPRESSURE (5 psi DESIGN)

| Shelter Level | Room | Number of Occupants | Incipient Failure Overpressure Face-on | | | | Catastrophic Failure Overpressure Face-on | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1-3 | 3-6 | 6-8 | 8-1 | 1-3 | 3-6 | 6-8 | 8-1 |
| Upper | A | 81 | 38 | 38 | 38 | 38 | 73 | 73 | 73 | 73 |
| | B | 81 | 38 | 38 | 38 | 38 | 73 | 73 | 73 | 73 |
| | C | 49 | 62 | 62 | 62 | 50 | 87 | 87 | 87 | 87 |
| | D | 49 | 62 | 62 | 62 | 62 | 87 | 87 | 87 | 87 |
| | E | 49 | 62 | 62 | 62 | 62 | 87 | 87 | 87 | 87 |
| | F | 49 | 62 | 50 | 62 | 62 | 87 | 87 | 87 | 87 |
| | G | 34 | 46 | 46 | 46 | 46 | 85 | 85 | 85 | 85 |
| | H | 0 | 46 | 46 | 46 | 46 | 85 | 85 | 85 | 85 |
| Lower | A | 81 | 65 | 65 | 65 | 65 | 88 | 88 | 88 | 88 |
| | B | 81 | 65 | 65 | 65 | 65 | 88 | 88 | 88 | 88 |
| | C | 49 | 140 | 140 | 140 | 140 | 576 | 576 | 576 | 576 |
| | D | 49 | - | - | - | - | - | - | - | - |
| | E | 49 | - | - | - | - | - | - | - | - |
| | F | 49 | 140 | 140 | 140 | 140 | 576 | 576 | 576 | 576 |
| | G | 25 | 69 | 69 | 69 | 69 | 150 | 150 | 150 | 150 |
| | H | 25 | 69 | 69 | 69 | 69 | 150 | 150 | 150 | 150 |

TABLE 1.13

ROOM FAILURE OVERPRESSURE (25 psi DESIGN)

| Shelter Level | Room | Number of Occupants | Incipient Failure Overpressure Face-on | | | | Catastrophic Failure Overpressure Face-on | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1-3 | 3-6 | 6-8 | 8-1 | 1-3 | 3-6 | 6-8 | 8-1 |
| Upper | A | 81 | 60 | 60 | 60 | 60 | 90 | 90 | 90 | 90 |
| | B | 81 | 60 | 60 | 60 | 60 | 90 | 90 | 90 | 90 |
| | C | 49 | 62 | 62 | 62 | 50 | 87 | 87 | 87 | 87 |
| | D | 49 | 62 | 62 | 62 | 62 | 87 | 87 | 87 | 87 |
| | E | 49 | 62 | 62 | 62 | 62 | 87 | 87 | 87 | 87 |
| | F | 49 | 62 | 50 | 62 | 62 | 87 | 87 | 87 | 87 |
| | G | 34 | 46 | 46 | 46 | 46 | 85 | 85 | 85 | 85 |
| | H | 0 | 46 | 46 | 46 | 46 | 85 | 85 | 85 | 85 |
| Lower | A | 81 | 109 | 109 | 109 | 109 | 111 | 111 | 111 | 111 |
| | B | 81 | 109 | 109 | 109 | 109 | 111 | 111 | 111 | 111 |
| | C | 49 | 140 | 140 | 140 | 140 | 576 | 576 | 576 | 576 |
| | D | 49 | - | - | - | - | - | - | - | - |
| | E | 49 | - | - | - | - | - | - | - | - |
| | F | 49 | 140 | 140 | 140 | 140 | 576 | 576 | 576 | 576 |
| | G | 25 | 69 | 69 | 69 | 69 | 150 | 150 | 150 | 150 |
| | H | 25 | 69 | 69 | 69 | 69 | 150 | 150 | 150 | 150 |

TABLE 1.14

ROOM FAILURE OVERPRESSURE (50 psi DESIGN)

| Shelter Level | Room | Number of Occupants | Incipient Failure Overpressure Face-on | | | | Catastrophic Failure Overpressure Face-on | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1-3 | 3-6 | 6-8 | 8-1 | 1-3 | 3-6 | 6-8 | 8-1 |
| Upper | A | 81 | 61 | 61 | 61 | 61 | 112 | 112 | 112 | 112 |
| | B | 81 | 61 | 61 | 61 | 61 | 112 | 112 | 112 | 112 |
| | C | 49 | 78 | 78 | 78 | 56 | 114 | 114 | 114 | 114 |
| | D | 49 | 78 | 78 | 78 | 78 | 114 | 114 | 114 | 114 |
| | E | 49 | 78 | 78 | 78 | 78 | 114 | 114 | 114 | 114 |
| | F | 49 | 78 | 56 | 78 | 78 | 114 | 114 | 114 | 114 |
| | G | 34 | 55 | 55 | 55 | 55 | 115 | 115 | 115 | 115 |
| | H | 0 | 55 | 55 | 55 | 55 | 115 | 115 | 115 | 115 |
| Lower | A | 81 | 138 | 138 | 138 | 138 | 173 | 173 | 173 | 173 |
| | B | 81 | 138 | 138 | 138 | 138 | 173 | 173 | 173 | 173 |
| | C | 49 | 175 | 175 | 175 | 175 | 936 | 936 | 936 | 936 |
| | D | 49 | - | - | - | - | - | - | - | - |
| | E | 49 | - | - | - | - | - | - | - | - |
| | F | 49 | 175 | 175 | 175 | 175 | 936 | 936 | 936 | 936 |
| | G | 25 | 86 | 86 | 86 | 86 | 238 | 238 | 238 | 238 |
| | H | 25 | 86 | 86 | 86 | 86 | 238 | 238 | 238 | 238 |

TABLE 1.15

SURVIVORS VERSUS OVERPRESSURE
Face-on 6-8 (3-1) (5 psi Design)

| Level | Room | Free Field Overpressure | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 38 | 46 | 62 | 65 | 69 | 73 | 85 | 87 | 88 | 140 | 150 | 576 |
| Upper | A | 81 | 62 | 25 | 19 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | B | 81 | 62 | 25 | 19 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | D | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | E | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | F | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | G | 34 | 34 | 20 | 17 | 14 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower | A | 81 | 81 | 81 | 81 | 67 | 53 | 11 | 4 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 81 | 67 | 53 | 11 | 4 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | D | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | E | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | F | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | G | 25 | 25 | 25 | 25 | 25 | 24 | 20 | 19 | 19 | 3 | 0 | 0 |
| | H | 25 | 25 | 25 | 25 | 25 | 24 | 20 | 19 | 19 | 3 | 0 | 0 |
| Total Survivors | | 800 | 762 | 674 | 635 | 552 | 468 | 274 | 242 | 234 | 202 | 194 | 98 |
| Percent of Total | | 100 | 95 | 84 | 79 | 69 | 59 | 34 | 30 | 29 | 25 | 24 | 12 |

TABLE 1.16

SURVIVORS VERSUS OVERPRESSURE
Face-on 6-8 (3-1) (25 psi Design)

| Level | Room | Free Field Overpressure | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 46 | 60 | 62 | 69 | 85 | 87 | 90 | 109 | 111 | 140 | 150 | 576 |
| Upper | A | 81 | 81 | 76 | 57 | 14 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 76 | 57 | 14 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | D | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | E | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | F | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | G | 34 | 22 | 20 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower | A | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | D | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | E | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | F | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | G | 25 | 25 | 25 | 25 | 20 | 19 | 18 | 13 | 12 | 3 | 0 | 0 |
| | H | 25 | 25 | 25 | 25 | 20 | 19 | 18 | 13 | 12 | 3 | 0 | 0 |
| Total Survivors | | 800 | 788 | 776 | 662 | 442 | 412 | 394 | 384 | 220 | 202 | 194 | 98 |
| Percent of Total | | 100 | 99 | 96 | 83 | 55 | 52 | 49 | 48 | 28 | 25 | 24 | 12 |

TABLE 1.17

SURVIVORS VERSUS OVERPRESSURE
Face-on 6-8 (3-1) (50 psi Design)

| Level | Room | Free Field Overpressure | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 55 | 61 | 78 | 86 | 112 | 114 | 115 | 138 | 173 | 175 | 238 | 936 |
| Upper | A | 81 | 81 | 54 | 41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 54 | 41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | D | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | E | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | F | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | G | 34 | 31 | 21 | 16 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower | A | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 45 | 0 |
| | D | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | E | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | F | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 45 | 0 |
| | G | 25 | 25 | 25 | 25 | 21 | 20 | 20 | 17 | 11 | 10 | 0 | 0 |
| | H | 25 | 25 | 25 | 25 | 21 | 20 | 20 | 17 | 11 | 10 | 0 | 0 |
| Total Survivors | | 800 | 787 | 733 | 658 | 414 | 399 | 398 | 392 | 218 | 216 | 188 | 98 |
| Percent of Total | | 100 | 98 | 92 | 82 | 52 | 50 | 50 | 49 | 27 | 27 | 24 | 12 |

TABLE 1.18

SURVIVORS VERSUS OVERPRESSURE
Face-on 8-1 (6-3) (5 psi Design)

| Level | Room | Free Field Overpressure | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 38 | 46 | 50 | 62 | 65 | 69 | 73 | 85 | 87 | 88 | 140 | 150 | 576 |
| Upper | A | 81 | 62 | 53 | 25 | 19 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | B | 81 | 62 | 53 | 25 | 19 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 33 | 29 | 24 | 19 | 3 | 0 | 0 | 0 | 0 | 0 |
| | D | 49 | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | E | 49 | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | F | 49 | 49 | 49 | 49 | 43 | 35 | 27 | 4 | 0 | 0 | 0 | 0 | 0 |
| | G | 34 | 34 | 31 | 20 | 17 | 14 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower | A | 81 | 81 | 81 | 81 | 81 | 67 | 53 | 11 | 4 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 81 | 81 | 67 | 53 | 11 | 4 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | D | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | E | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | F | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | G | 25 | 25 | 25 | 25 | 25 | 25 | 24 | 20 | 19 | 19 | 3 | 0 | 0 |
| | H | 25 | 25 | 25 | 25 | 25 | 25 | 24 | 20 | 19 | 19 | 3 | 0 | 0 |
| Total Survivors | | 800 | 762 | 741 | 658 | 621 | 541 | 460 | 273 | 242 | 234 | 202 | 194 | 98 |
| Percent of Total | | 100 | 95 | 93 | 82 | 78 | 68 | 58 | 34 | 30 | 29 | 25 | 24 | 12 |

TABLE 1.19

SURVIVORS VERSUS OVERPRESSURE
Face-on 8-1 (6-3) (25 psi Design)

| Level | Room | Free Field Overpressure | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 46 | 50 | 60 | 62 | 69 | 85 | 87 | 90 | 109 | 111 | 140 | 150 | 576 |
| Upper | A | 81 | 81 | 81 | 76 | 57 | 14 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 76 | 57 | 14 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 36 | 33 | 24 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | D | 49 | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | E | 49 | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | F | 49 | 49 | 49 | 49 | 35 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | G | 34 | 31 | 22 | 20 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower | A | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | D | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | E | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | F | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 48 | 0 |
| | G | 25 | 25 | 25 | 25 | 25 | 20 | 19 | 18 | 13 | 12 | 3 | 0 | 0 |
| | H | 25 | 25 | 25 | 25 | 25 | 20 | 19 | 18 | 13 | 12 | 3 | 0 | 0 |
| Total Survivors | | 800 | 797 | 775 | 760 | 665 | 441 | 412 | 394 | 384 | 220 | 202 | 194 | 98 |
| Percent of Total | | 100 | 99 | 97 | 95 | 83 | 55 | 52 | 49 | 49 | 28 | 25 | 24 | 12 |

TABLE 1.20

SURVIVORS VERSUS OVERPRESSURE
Face-on 8-1 (6-3) (50 psi Design)

| Level | Room | Free Field Overpressure | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 55 | 56 | 61 | 78 | 86 | 112 | 114 | 115 | 138 | 173 | 175 | 238 | 936 |
| Upper | A | 81 | 81 | 81 | 54 | 41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 54 | 41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 45 | 30 | 24 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | D | 49 | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | E | 49 | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | F | 49 | 49 | 49 | 49 | 38 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | G | 34 | 33 | 31 | 21 | 16 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower | A | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | B | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 81 | 0 | 0 | 0 | 0 |
| | C | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 45 | 0 |
| | D | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | E | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| | F | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 45 | 0 |
| | G | 25 | 25 | 25 | 25 | 25 | 21 | 20 | 20 | 17 | 11 | 10 | 0 | 0 |
| | H | 25 | 25 | 25 | 25 | 25 | 21 | 20 | 20 | 17 | 11 | 10 | 0 | 0 |
| Total Survivors | | 800 | 799 | 793 | 714 | 644 | 413 | 399 | 398 | 392 | 218 | 216 | 188 | 98 |
| Percent of Total | | 100 | 100 | 99 | 89 | 81 | 52 | 50 | 50 | 49 | 27 | 27 | 24 | 12 |

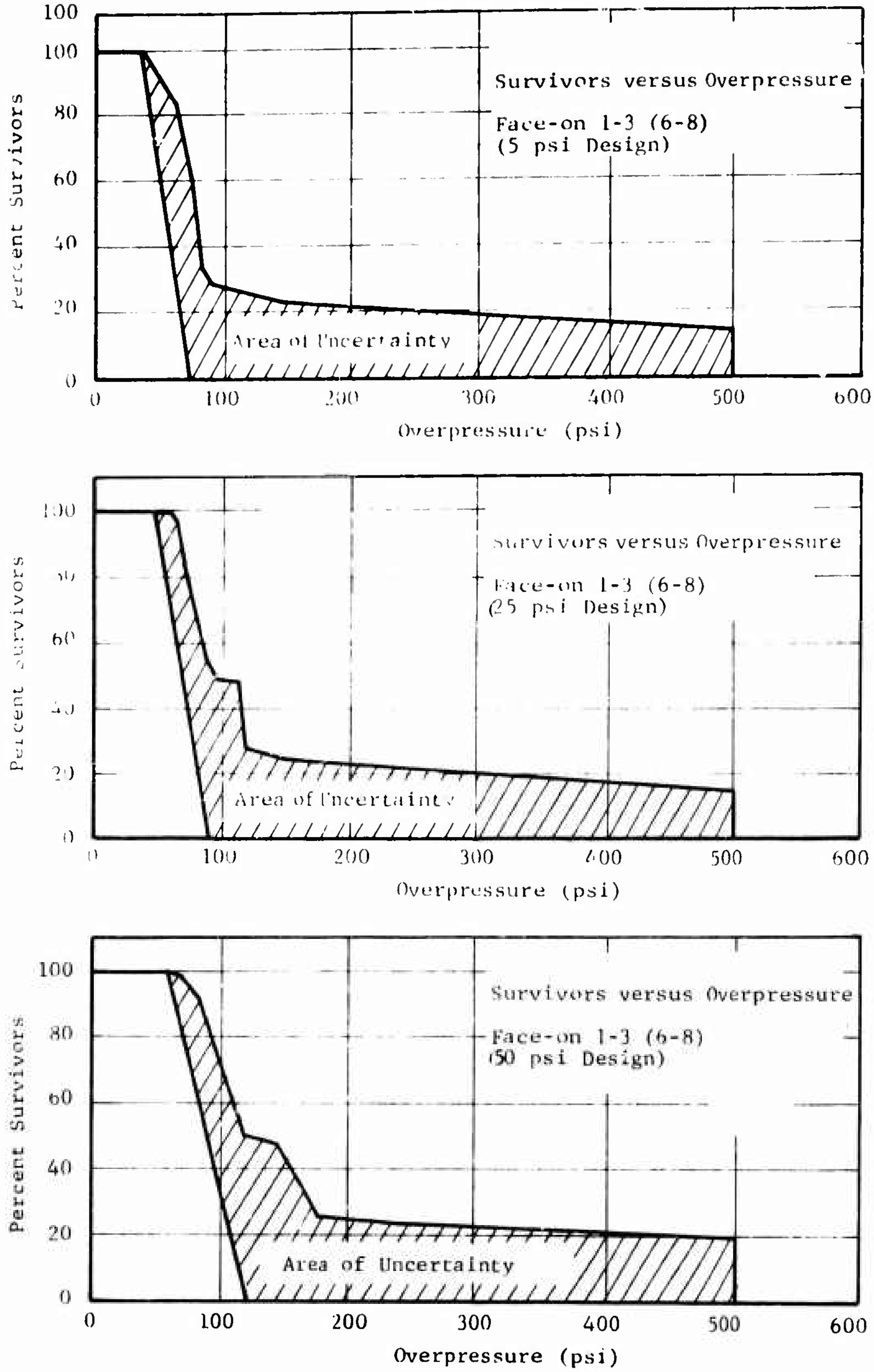



Fig. 1.15 SURVIVABILITY FUNCTIONS FOR EXPRESSWAY GRADE SEPARATION SHELTERS

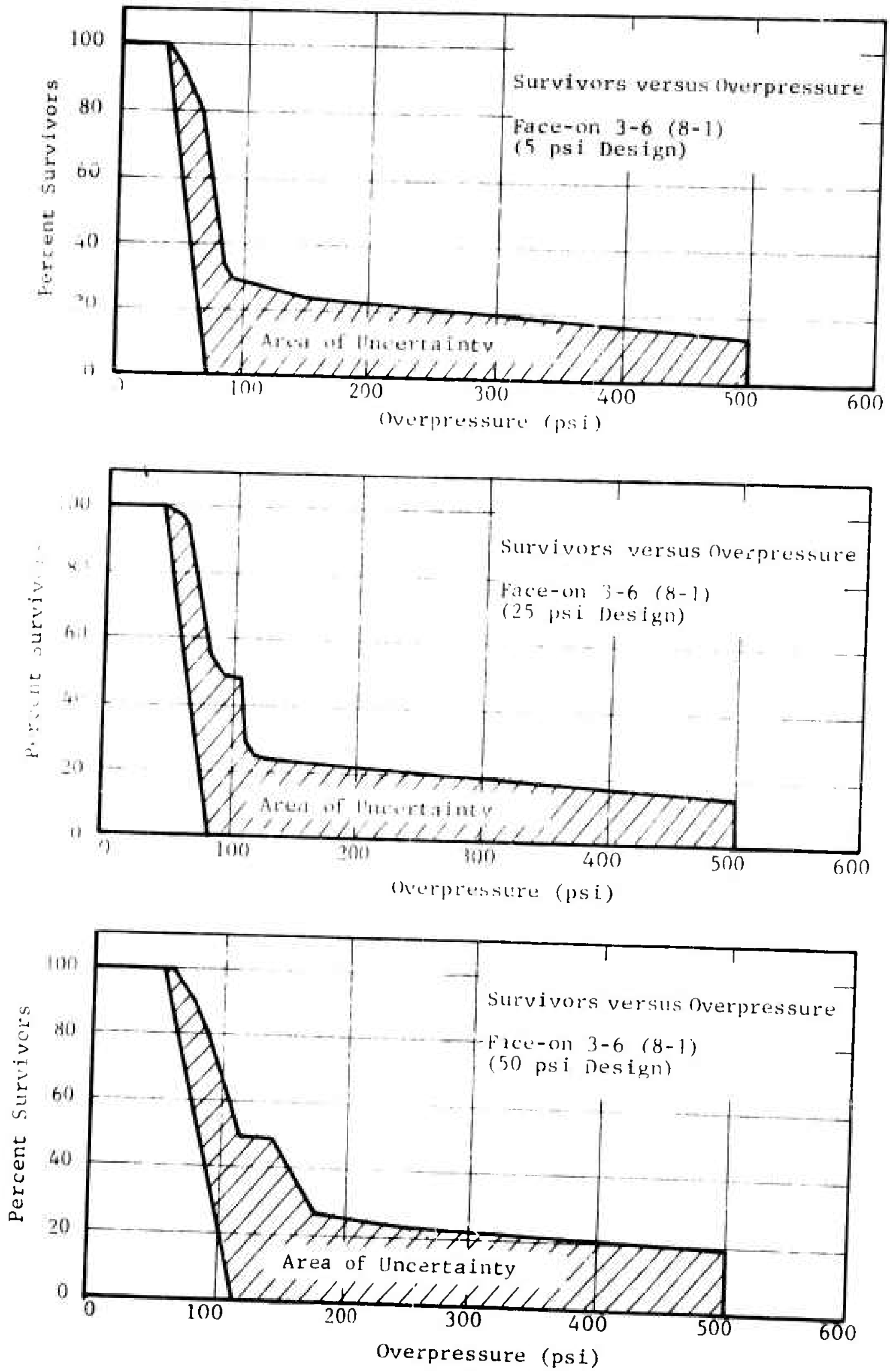



Fig. 1.15 SURVIVABILITY FUNCTIONS FOR EXPRESSWAY GRADE SEPARATION SHELTERS (Concluded)

### 1.1.5 Judiciary Square Passenger Station (Ref. 67)

The Judiciary Square Passenger Station is part of the proposed Washington Metropolitan Area Transit Authority subway system and at this time (1971) it is in the construction stage. Physical characteristics of the station are described in Appendix A, Vol.II, and in this subsection the survivability potential for several sheltering options is discussed.

This passenger station was considered in a shelter study performed by B. Shimizu et al of Holmes and Narver (Ref. 68). The study conducted by Shimizu is generally a well conceived and executed, all-inclusive feasibility analysis which considered the hardness and habitability aspects of this passenger station. In the course of the present effort this passenger station was analyzed to determine its blast resistance and the study performed by Shimizu was reviewed. Results and conclusions of this effort are discussed.

A subway system has long been viewed as a potentially favorable existing sheltering resource. Indeed it possesses apparent sheltering advantages some of which are:

1. Large areas of protected below-grade space
2. Contains large numbers of people at peak rush hours of the day
3. Strong construction relative to most conventional structures
4. Large numbers of connecting entrances and exits to key portions of the city
5. Temperatures remain fairly constant during the year.

Some corresponding disadvantages are:

1. The bulk of ventilation is provided by the piston action of passenger trains. In an emergency situation trains would not be running. The large, interconnected spaces would be difficult and thus costly to ventilate.

2. Accommodations (toilets, water, first aid, etc.) are minimum and therefore are not adequate for large numbers of people for a prolonged stay.
3. Space for storing adequate quantities of shelter supplies generally does not exist. The use of available space for this purpose would interfere with the normal function.
4. Subway portions passing under rivers or below the water table could become untenable in the event structural damage is experienced. The extent of structural damage capable of creating untenable conditions need not be excessive.
5. Maintaining a workable shelter capacity, posturing of shelterees and maintaining order may be a distinct problem. This may be avoided by designing and implementing an enforceable shelter use plan.
6. Even though there is an advantage of having numerous entranceways, there remains the problem of being able to close them in an effective and economic manner when high overpressures are anticipated.
7. Subways are currently restricted to a fairly small number of large cities and therefore the number of spaces available nationally when compared to other sheltering resources is quite small.

Like most conventional structures which are built with a specific function in mind, subways are not ideally suited for sheltering purposes. However they do exist, and they constitute a real sheltering resource. For the planning of effective shelter systems it is useful to know the extent of protection afforded by them.

The analysis performed in order to determine the blast resistance of the Judiciary Square Passenger Station is described, and these results are used in the subsequent section to estimate survivability for several sheltering options.

1.1.5.1 Analysis of Structural Behavior

The analytic approach used in determining the magnitude of surface overpressure at which the arch is in the state of incipient failure is presented in Chapter Two, Vol.II of this report. It is based on a single degree of freedom model of the arch and a portion of the surrounding soil. Such an analysis requires a resistance function

(load-displacement relationship) for a point on the structure. In the present analysis the crown of the arch was selected and its load-deflection relationship was determined using an existing plane stress, nonlinear, finite element computer program (Ref. 24). Since the structure is long in comparison to its largest cross-sectional dimension, the plane stress assumption is sufficiently accurate for the intended purposes. The analytical model used in determining the resistance function is shown in Fig. 1.16. The model includes the arch and a portion of the surrounding medium.

The specific cross section of the arch analyzed herein is located at a survey-station 37 + 70 (Appendix A, VOL. II). At this location the depth of the arch crown is 5 ft-5 in. below the ground surface, which is the shallowest position for this passenger station. At this location the arch is most vulnerable to the effects of surface blast overpressure.

It is mentioned (Appendix A, Vol. II) that the arch is of waffle slab construction. In determining its resistance function a solid cross section having an equivalent stiffness was used. The properties of concrete were taken as: density - 150 lbs/cu ft, modulus of elasticity (E) - 3,000,000 psi, Poisson's ratio - 0.13, ultimate compressive strength ($f_c'$) - 2500 psi.

In the vicinity of this arch section the boring log (Ref. 67) provides the following information:

| Layer | Depth below Ground Surface | Soil Description |
|---|---|---|
| 1 | 0 - 8 ft | Fill |
| 2 | 8 ft - 43 ft | Medium to fine sand, light brown to light grey |
| 3 | 43 ft - 67 ft | Medium to fine sand, light grey to dark grey |
| 4 | 67 ft - 71.5 ft | Silty sand with layers of lignite |

Since the passenger station would be constructed in a cut, the soil in its immediate vicinity and above its base would be a compacted fill.

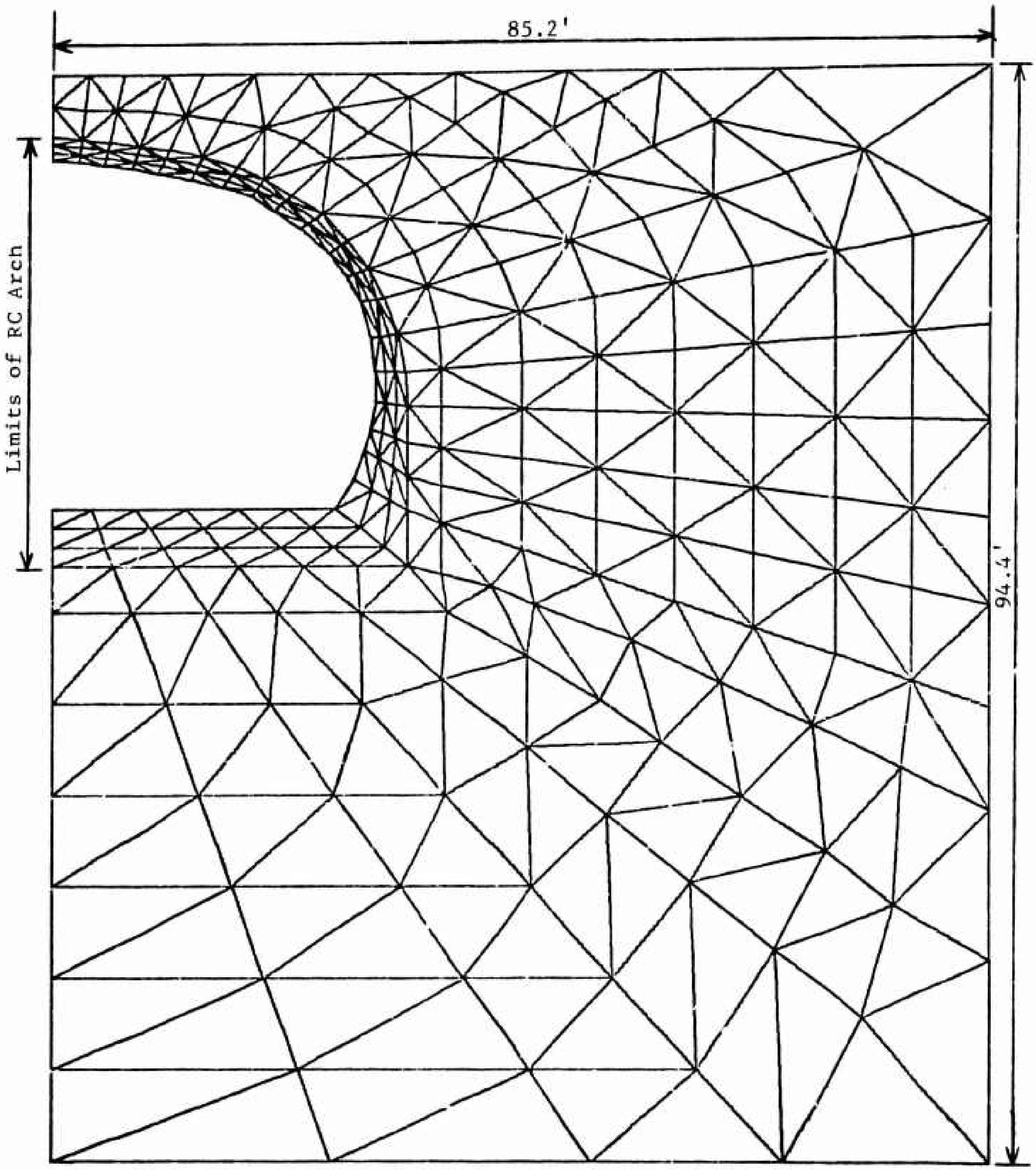



Fig. 1.16 ANALYTICAL MODEL OF PASSENGER STATION ARCH

This fill would most probably be a mixture of layers 1 and 2 in which the properties of the second layer would be dominant. Based on this reasoning and the boring log data given, the medium shown in Fig. 1.16 was divided into three irregular layers having these properties:

| Layer | Depth below Ground Surface | Soil Modulus (psi) (Ref. 69) | Poisson's Ratio (Ref. 69) | Mass Density (Ref. 70) |
|---|---|---|---|---|
| 1 | 0 - 43 ft | 7500 | 0.38 | 0.000168 |
| 2 | 43 ft - 67 ft | 12000 | 0.36 | 0.000188 |
| 3 | 67 ft - 94.41 ft | 1500 | 0.34 | 0.000202 |

Soil densities given are averages for the given soil in the dry and the saturated states. For each layer the plastic modulus used was 10 percent of the elastic modulus given. Using the model, material properties and the method described, the static resistance function for the arch section was determined and is shown in Fig. 1.17 and represents the deflection history of the crown. The choice of using a point on the crown as a reference point is arbitrary. In the subsequent dynamic analysis performed, effective strains were monitored for each element of the arch section. Incipient failure overpressure was determined when the effective strain at any section through the arch exceeded 0.003 in./in. Failure occurred at a section approximately 25 degrees from the horizontal. It will be noted that unlike the previous arch analyses performed in this study the entire arch, including foundations, was allowed to move vertically, subject to the surface loading. Results of this analysis are discussed in Subsection 1.1.5.2.

1.1.5.2 <u>Sheltering Potential - Protective Capabilities and Costs</u>

In the study performed by Shimizu (Ref. 68) two sheltering options were considered.

<u>Sheltering Option 1</u>. -- This option is based on the hardness of the proposed passenger station. The hardness is estimated at 25 psi. Even though not specifically stated, we assume that it refers to 100 percent survivors at this overpressure level.

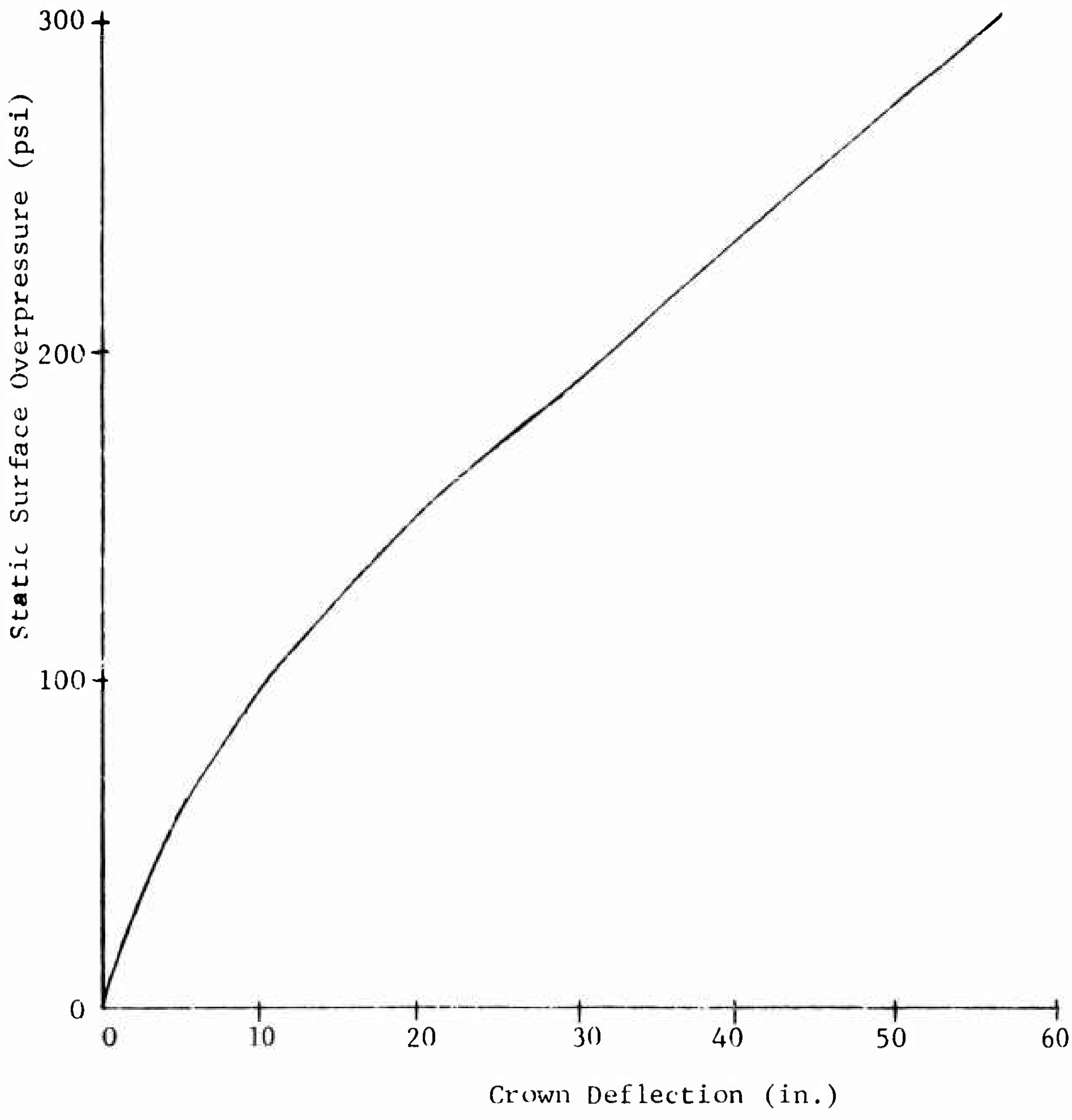



Fig. 1.17 STATIC RESISTANCE FUNCTION FOR PASSENGER STATION ARCH

This sheltering option includes:

1. Auxiliary shelter spaces to be used for food storage, office and first aid station, latrine, water and fuel storage, bunk storage, and mechanical and electrical equipment.
2. Air conditioning, ventilation piping and plumbing
3. Power, lighting and diesel generators
4. Blast doors and valves

Auxiliary spaces constitute additional construction and would consist of tunnels similar to those used for the train tunnel. Four blast doors are included. Two for the main entrances and two in the tunnels, i.e., one at each end of the passenger station. The blast doors were designed to match the hardness of the proposed passenger station. Those at the main entrances would be of the tilt-up type while those in the tunnel would be sliding doors.

Sheltering Option 2.--This sheltering option is identical to the one above except that the entire structure, i.e., passenger station shell, a portion of the tunnels at each end of the station and entrance and tunnel closures would be hardened to 50 psi free-field overpressure. Corresponding sheltering costs (given by Shimizu) for the two options are given in Table 1.21. These are based on the assumption that shelter is considered in the initial planning stage of the subway. The costs are for the year 1969 and presumably for the District of Columbia.

The study performed by Shimizu was reviewed in the course of the effort described. It is felt that the sheltering options considered are well conceived and certainly adequate. However, it is felt that the protective capabilities of the passenger station structure were grossly underestimated. On the basis of the analysis performed herein and described earlier, the survivability ratings are given in Fig. 1.18. for the proposed conventional structural system. The structure has substantial structural resistance which is certainly in excess of 25 psi.

TABLE 1.21

SUBWAY PASSENGER STATION SHELTERING COSTS (Ref.68), OPTIONS 1 AND 2

| Item | Option 1 Proposed Design (Rated at 25 psi) | Option 2 50 psi Design |
|---|---|---|
| 1. Structural: | | |
| a. Passenger station | - | 696,000 |
| b. Portion of train tunnels | - | 147,000 |
| c. Auxiliary spaces: Tunneled structure and underground storage tanks | $ 1,643,000 | $ 1,833,000 |
| 2. Mechanical: Air conditioning, ventilation piping and plumbing | 1,845,000 | 1,845,000 |
| 3. Electrical: Power, lighting and diesel generators | 367,000 | 367,000 |
| 4. Special equipment: Blast doors and valves | 1,489,000 | 1,544,000 |
| Total | $ 5,344,000 | $ 6,432,000 |
| 6. Shelter area: 68,000 sq ft | | |
| 7. Unit Cost | $ 78.50 | $ 94.60 |

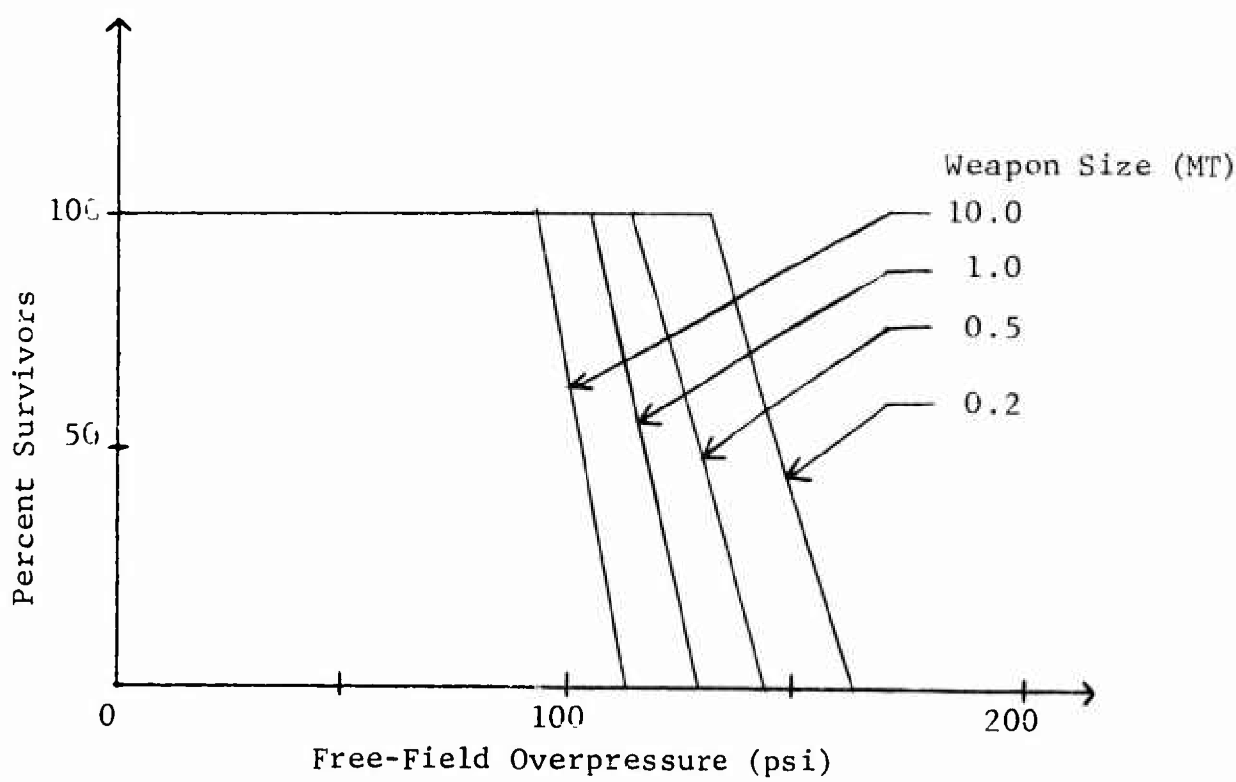



Fig. 1.18 SURVIVABILITY FUNCTIONS FOR PASSENGER STATION ARCH

On the basis of results obtained, Cost Option 1 (Table 1.21) should be considered in the light of survivability ratings given in Fig. 1.18. The 50 psi design was not analyzed in the course of this effort due to lack of a detailed description.

When compared to other shelters considered in this study, the sheltering option described is quite expensive. It is a very complete option which takes into account every contingency. The major costs are in providing auxiliary spaces and rather elaborate mechanical equipment. A more austere option is described here.

In the study performed by Shimizu the shelter portion consisted of the passenger station and a portion of the train tunnel on either side of the station. Blast closures were provided in the train tunnel and at the main entrances. It is felt that placing people in the train tunnel is undesirable due to ventilation requirements. An emergency ventilation system which is adequate for the passenger station and a portion (about 600 ft) of the tunnel is obviously costly. However a minimum ventilation system for the passenger station alone can be installed (in the initial construction stage) for a cost of $200,000. This would include a 1000 KVA distribution with thirty 10-hp fans. The same generator system would also provide minimum lighting.

Since the shelter has an inherent blast resistance in excess of 100 psi free field, and since the total area of openings leading into the station is large (Appendix A, Vol.II), blast closures would need to be provided for overpressures in excess of about 30 to 40 psi. Such closures would be required at the main entrances and the main ventilation structures but not in the train tunnels. The total cost of blast closures complementing the survivability ratings given in Fig. 1.18 is estimated at $400,000.

The major difficulty in providing blast closures for the main entrances and elsewhere is that these must not interfere with the conventional function and should blend with the station layout. In the present case this is difficult and therefore costly to accomplish. It should be noted that the main entranceways for this

passenger station are larger and more elaborate than most existing subway passenger stations in this country.

Sheltering costs for the more austere sheltering Option 3 are given in Table 1.22. It is assumed that only the passenger station (mezzanines, platforms and track area between platforms) is used for sheltering purposes. The total shelter area is 46,700 sq ft.

TABLE 1.22

SUBWAY PASSENGER STATION SHELTERING COSTS, OPTION 3

| | Item | Cost |
|---|---|---|
| 1 | Mechanical and Electrical Equipment | $200,000 |
| 2 | Special Equipment: Blast Closures (Main Entrances Only) | 400,000 |
| 3 | OCD Water Containers (Convertible to Chemical Toilets) | 3,280 |
| | Total | $603,280 |
| 4 | Total Shelter Area: 46,700 sq ft | |
| 5 | Unit Cost | $ 12.90 |

In the event this shelter is used for overpressure levels less than about 40 psi, blast closures may be omitted. The corresponding unit cost becomes $4.35.

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